2015

Spatial Variability of Saline and Sodic Soils in the Black Glaciated Region of the Northern Great Plains, USA

Rachel K. Owen

South Dakota State University

SPATIAL VARIABILITY OF SALINE AND SODIC SOILS IN THE BLACK GLACIATED REGION OF THE NORTHERN GREAT PLAINS, USA

BY

RACHEL K. OWEN

A thesis submitted in partial fulfillment of the requirements for

Master of Science

Major in Plant Science

South Dakota State University

2015

SPATIAL VARIABILITY OF SALINE AND SODIC SOILS IN THE BLACK GLACIATED REGION OF THE NORTHERN GREAT PLAINS, USA

This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Plant Science degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Douglas D. Malo, Ph.D.
Major/Thesis Advisor Date

David Wright, Ph.D.
Head, Department of Plant Science Date

Kinchel C. Doerner, Ph.D.
Dean, Graduate School Date

ACKNOWLEDGEMENTS

This project would not have been possible without the gracious help of advisors, mentors, friends, family, grower-cooperators, and many others. First, I'd like to acknowledge the USDA-NRCS CIG project 69-3A75-12-185 and the South Dakota Corn Utilization Council. Not only did they provide funding to make this project possible, but I greatly appreciate the opportunities they gave me to work with NRCS soil scientists, SD Corn Council employees, and especially the farmers of South Dakota. Much of what I have learned through this project was obtained while I was talking with growers and helping them to understand the salt problems that were occurring in their fields.

Next, I would like to thank Greg Tople, Jim Millar, Kenny Sehlman, Jerry West, Roger and Grant Rix, and David Gillan. Not only did these growers allow me to collect my data from their fields, but they provided constant support whenever I needed assistance. Also, I would like to thank Greg Tople and David Gillan again for hosting the Saline and Sodic Soil Extension Days during summer 2014. The extension days were an incredible opportunity for me to talk with growers and practice explaining my research to others.

My work would also not have been possible without the help of my advisors and committee members – Doug Malo, Tom DeSutter, Cheryl Reese, David Clay, Sandeep Kumar, and Karla Hunter. Not only did they provide technical support and feedback for my research and course work, but they constantly encouraged me to do my best and be an active member of my department and scientific community. I feel so fortunate to have been able to work with Dr. Doug Malo. He has been a terrific mentor for both professional and personal life. Also, I would like to thank Gregg Carlson, Sharon Clay,

Graig Reicks, Stephanie Hanson, and the rest of the Department of Plant Science at South Dakota State University, as well as Kevin Horsager and countless others in the Department of Soil Science at North Dakota State University for their help and support.

My parents, Joel and Dina Johnson, have always encouraged me to pursue my dreams, a gift far greater than any physical object. Due to their support, I have always felt capable of doing whatever I set my mind to. I would also like to thank my fiancé Karl Kerns for his support and encouragement while I have been in South Dakota, and for helping me to always keep faith and family at the top of my priorities. In addition to my parents and Karl, I'd also like to thank Andrew and Lindsey Owen, the entire Andersen family, and Steve and Becky Kerns for being incredibly supportive of my professional goals.

I would like to acknowledge Tulsi Kharel and Girma Birru for their support in my research, helping me with field work, and often times treating me like a younger sister. I could not have asked for better graduate students to work with on the soil salt project. Many thanks to my classmates and friends – Sagar Gautam, Brianna Wegner, Heidi Myer, Karly Regan, Rebecca Helget, Saroop Sandhu, Deepak Joshi, Eric Mbonimpa, Nick Schiltz, and Hannah Wilkerson – for helping me with lab work, field work, and homework, but most importantly, for keeping me sane.

Above all, I must give all credit to God for leading me down the path of academics and guiding me through this journey.

TABLE OF CONTENTS

ABBREVIATIONS

a – Range of spatial dependence
C – Partial Sill Semi-variance
C_0 – Nugget Semi-variance
℃ – Centigrade
Ca^{2+} - Calcium
CEC – Cation Exchange Capacity
cm – centimeters
CV – Coefficient of Variation
dS – DeciSiemens
e – Saturated Paste Extraction
E – East
EC – Electrical Conductivity
g – grams
GPS – Global Positioning System
h – lag distance
IDW – Inverse Distance Weighting
L - Liters
m – meters
Mg^{2+} - Magnesium
mL – milliliters
mm – millimeters
$mmole_c$ – Millimoles of charge
MLRA – Major Land Resource Area
n – number of samples
N – North
Na^{+} - Sodium
ND – North Dakota, USA
NE – Northeast
NRCS - Natural Resources Conservation Service
NW – Northwest
R^2 – Coefficient of Determination
RMSE – Root Mean Square Error
S – South
SAR – Sodium Adsorption Ratio
SD – South Dakota, USA
SE – Southeast
SW – Southwest
TSA – Total Soluble Anions
TSC – Total Soluble Cations
USA – United States of America
USDA – United States Department of Agriculture
W – West
w/w – Weight per Weight Ratio
γ – Semi-variance
1:1 – 1:1 Soil:Water Ratio

LIST OF FIGURES

CHAPTER 2 Page

LIST OF TABLES

ABSTRACT

SPATIAL VARIABILITY OF SALINE AND SODIC SOILS IN THE BLACK GLACIATED REGION OF THE NORTHERN GREAT PLAINS, USA

RACHEL K. OWEN

2015

Recent (1990-2014) increases in salt affected soils in the Northern Great Plains states of South Dakota (SD) and North Dakota (ND), MLRA 55B and 55C, have prompted more intensive research on groundwater derived saline and sodic soil characteristics in semi-humid and humid climates. Past research has focused on salinity and sodicity in irrigated agricultural systems in semi-arid and arid climates. Due to the disconnect between prior research and current problems in this region, it is necessary to assess widely used laboratory methods, and determine if short cuts can be used for rapid evaluation. The objectives of this research were: 1) to establish a relationship between soil electrical conductivity (EC) and the total soluble cations (TSC); 2) establish the relationships between EC of saturated paste extraction solutions, 1:1, and 1:5 soil:water extraction dilutions; and 3) to assess the field scale spatial distribution of saline and sodic soil properties in order to identify soils at high risk of developing saline and sodic issues in the future. EC, soluble sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) and the sodium adsorption ratio (SAR) were measured for soil samples collected from four sites across SD and N research established a robust linear relationship between EC and TSC of TSC = 13.54 *EC – 0.29 (R^2 = 0.88). Based on the results of the second study, not only can linear regression relationships be developed between saturated paste extractions and various soil:water dilutions, but a non-linear relationship can also be established to

predict the salinity parameters based on the dilution factor. Finally, the third study found that while the prediction maps generated using ordinary kriging were not statistically significant, they showed that the salt affected soil area increased with depth. Soils that lack saline and sodic soil problems at the surface, but have moderate saline and sodic soil problems in the subsurface should be considered high risk for developing more severe limitations in the future when capillary and groundwater rise could bring soil solutes to the soil surface.

CHAPTER 1
INTRODUCTION AND LITERATURE REVIEW

Lab Techniques for Saline and Sodic Soil Analysis

Salt affected soils are a major limitation to crop production in the Northern Great Plains and worldwide (Franzen, 2007). Producers must be able to understand the saline and sodic soil problems in their fields in order to make proper management decisions, such as crop selection, amendment application (for sodic and saline-sodic soils), and water management. Crop selections are based on salt-tolerance recommendations and perennial vegetation can be used to reclaim salt affected soils (Franzen, 2007). Chemical amendments, such as gypsum, may be needed to replace sodium on the cation exchange capacity (CEC) sites and leach excess sodium (DeSutter, 2008). In the Northern Great Plains, salt affected soils are often the result of salty groundwater near the soil surface (Franzen, 2007), so subsurface drainage may also be considered to manage salt affected soils (US Salinity Laboratory Staff, 1954). Research and extension publications typically make recommendations for salt-affected soil management using electrical conductivity (EC) and sodium adsorption ratio (SAR).

Globally, EC is a common index in assessing soil salinity. The ability of a soil solution to conduct electricity is directly related to the total amount of soluble cations (TSC) and anions (TSA) contained in a solution. EC readings can be affected by soil moisture content (Vaughan, 1995), texture (Sudduth, et al., 2005), and mineral composition (US Salinity Laboratory Staff, 1954). The EC has been used to estimate the total dissolved cations in the solution. In 1954, the US Salinity Laboratory established the relationship of approximately 10:1 for EC (dS m^{-1}) to TSC ($mmole_c$ L^{-1}) , and since, this

ratio has been used to simplify other salinity calculations, especially those involving the relative proportions of monovalent and divalent cations in the soil, and can serve as a quick field scale assessment of salinity issues (Rhoades, 1982; US Salinity Laboratory Staff, 1954). The total dissolved cation values are used to calculate the SAR. SAR is calculated using Equation 1.1:

$$SAR = \frac{[Na^+]}{\left(\frac{[Ca^{2+}] + [Mg^{2+}]}{2}\right)^{1/2}} \quad (1.1)$$

where SAR is the sodium adsorption ratio, $[Na^+]$ is the concentration of soluble sodium, $[Ca^{2+}]$ is the concentration of soluble calcium, and $[Mg^{2+}]$ is the concentration of soluble magnesium. In this calculation, the EC×10 value is used to calculate the approximate amount of $Ca^{2+} + Mg^{2+} + Na^+$ contained in solution. The sum of Ca^{2+} and Mg^{2+} is determined by subtracting Na^+ from the EC×10 value.

This approach was based on the salt affected soils in the 17 Western States and Hawaii (US Salinity Laboratory Staff, 1954). Crucial differences exist between the soils studied by Rhoades (1982) and the US Salinity Laboratory Staff (1954) and the salt-affected soils in the Central and Southern Black Glaciated Plains in South Dakota and North Dakota, USA (MLRA Regions 55B and 55C [NRCS, 2014]). One of the primary differences is the source of the salts. In the Northern Great Plains, salinity occurs due to the subsurface transport of salts with capillary water to the surface soil, whereas in the arid and semi-arid regions of the west salts are provided with irrigation water. The soils of the Black Glaciated Plains were formed in till that overlays Cretaceous marine shale from a prehistoric ocean, so groundwater brings salts from the shale bedrock to the glaciated surface soils (Daniels, 1987). These critical differences suggest that salt

identification criteria developed for surface irrigated agricultural systems might have limited applications for the Northern Great Plains.

In laboratory studies done in South Dakota, with soils affected by groundwater salinity, the 10:1 relationship between EC and TSC did not hold true (Wilkerson et al., 2014). Studies done in Canada, where groundwater salinity is prevalent as well, have also found that the original relationship does not work and have created new models for relating EC and TSC (Chang, 1983).

There are two main reasons to establish a robust relationship between EC and TSC. First, indirect measurements of EC, such as electromagnetic induction with EM38 (Geomatrix Earth Science Ltd., 2014) or Veris (Veris Technologies, 2014) technology, are quick ways to assess soil salinity on a field scale (Rhoades, 1982). Next, research institutions and soil testing laboratories can use the relationship between EC and TSC to estimate the SAR.

Traditionally, EC and SAR have been measured using saturated paste extraction methods (Rhoades, 1982; US Salinity Laboratory Staff, 1954), but this procedure can be time consuming and tedious. Due to the time limitations, many soil testing labs are using simplified methods to analyze soil EC and Na^+ content. Survey results of soil testing labs in Fall 2013 (Appendix 1) showed that most labs use a 1:1 soil:water (w/w) dilution extraction (Rhoades, 1982) to measure EC and report Na^+ content as the percent Na^+ of the base saturation, determined using an ammonium acetate extraction method (Chapman, 1965). These different procedures cause discrepancies between values reported from research and extension publications and the soil testing results, which can cause confusion for producers and natural resource managers.

Extensive research has been done to establish the relationship between EC determined from saturated paste extractions (EC_e) and EC determined from soil:water dilutions ($EC_{1:1}$, $EC_{1:2}$, $EC_{1:2.5}$, $EC_{1:5}$). Franzen (2007) found the relationship for medium textured soils in North Dakota, USA to be $EC_e = 3.01EC_{1:1} - 0.77$. Hogg and Henry (1984), found the regression equations between methods to be $EC_e = 1.62EC_{1:1} - 0.24$ and $EC_e = 2.35EC_{1:2} - 0.36$ for medium textured soils in Saskatchewan, Canada. In Oklahoma, USA, Zhang, et al. (2005) determined that the regression model for predicting EC_e was $EC_e = 1.85EC_{1:1}$ when the intercept was forced through zero. Khorsandi and Yazdi (2011) found a relationship of $EC_e = 5.60EC_{1:5} - 4.37$ for soils with gypsum in the Yazd Province of Iran. He, et al. (2013) found that $EC_e = 2.74EC_{1:5} + 3.01$ in North Dakota, USA. Slavich and Petterson (1993) concluded that the best fit model for soils in the Riverine Plain, Australia was $EC_e = fEC_{1:5}$ where $f = 2.46 + 3.03/\theta SP$ and θSP indicates the water content of the saturated paste extraction. Finally, Sonmez, et al. (2008) looked at several different soil:water dilutions in Antalya, Turkey and found the following models were best suited in medium textured soils: $EC_e = 2.15EC_{1:1} - 0.44$, $EC_e = 3.84EC_{1:2.5} + 0.35$, and $EC_e = 7.58EC_{1:5} + 0.06$.

While many relationships have been found to predict EC_e using various soil:water dilutions, the results are not consistent, indicating regional variability. Also, little work has been done to measure soluble cations and predict sodium content with different soil:water dilutions. Sonmez, et al. (2008) outlined the models that have been established for soluble cation concentrations. For linear regression, the slopes of these models ranged from 0.95 to 2.78 for Na^+, 0.7 to 2.25 for Ca^{2+}, and 0.7 to 1.75 for Mg^{2+} when predicting the saturated paste extraction concentration using a 1:1 soil:water extraction

concentration. A model predicting SAR_e would be proportional to the soluble cation concentration models and would allow soil testing laboratories to report the soil sodium content in a format that producers could interpret and apply to their management practices.

Spatial Analysis of Saline and Sodic Soil Properties

In addition to understanding how the various saline and sodic soil properties are related to one another and to crop production, it is important to understand the spatial distribution of saline and sodic soil properties. The origin of soil salts in the Northern Great Plains differs from that of most saline and sodic soils studied, so research is needed to characterize these soils. One of the primary differences is the source of the salts. In the Northern Great Plains, salinity occurs due to the subsurface transport of salts with capillary water to the surface soil, whereas in the arid and semi-arid regions of the west salts are provides with irrigation water. The soils of the Black Glaciated Plains were formed in glacial till that overlays Cretaceous marine shale from a prehistoric ocean, so groundwater brings salts from the shale bedrock to the glaciated surface soils (Daniels, 1987). These critical differences suggest that salt identification criteria developed for surface irrigated agricultural systems will have limited applications for the Northern Great Plains.

Previous studies have examined the spatial distribution of soil salinity (Corwin, et al., 2003; Douaik, et al., 2005; Ganjegunte and Braun, 2011; Guo, et al., 2013; Li, et al., 2013; Li, et al., 2015; Rhoades, et al., 1990; Taghizadeh-Mehrjardi, et al., 2014), but in order to understand why this study is needed, we must consider why the spatial

distribution of salts in groundwater derived salt affected soils is different from past studies. According to Provin and Pitt (2012), salt buildup can occur in five different conditions including irrigating with water high in salts, in soils with poor drainage allowing for evaporation, in soils naturally high in salts, in areas where the water table is shallow, and in seepage zones. Soils in the Northern Great Plains are unique in that they are medium to fine textures, causing poor drainage at times, the soils themselves are naturally high in salts from the parent materials, and the water table is shallow. The mechanics of water and salt movement are then also unique in these soils compared to traditionally studied saline and sodic soils.

OBJECTIVES

Study 1

The objective of this study was to establish a relationship between EC and TSC that would fit soils throughout the Central and Southern Black Glaciated Plains of South Dakota and North Dakota (MLRA 55B and 55C).

Study 2

The primary objective of this study was to determine the relationship between EC, Na^{+}, Ca^{2+}, Mg^{2+}, and SAR measured using saturated paste extraction methods, and 1:1 and 1:5 soil:water dilution extraction methods.

Study 3

The objectives of this study were to establish a baseline field scale spatial distribution of EC, Na^{+}, Ca^{2+}, Mg^{2+}, and SAR at two sites in Eastern South Dakota.

REFERENCES

Chang, C., T.G. Sommerfeldt, J.M. Carefoot, and G.B. Schaalje. 1983. Relationships of electrical conductivity with total dissolved salts and cation concentration of sulfate-dominant soil extracts. Canadian Journal of Soil Science 63: 79-86.

Chapman, H.D. 1965. Cation-Exchange Capacity. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. ACSESS. p. 891-901.

Corwin, D.L., S.R. Kaffka, J.W. Hopmans, Y. Mori, J.W. van Groenigen, C. van Kessel, et al. 2003. Assessment and field-scale mapping of soil quality properties of a saline-sodic soil. Geoderma 114: 231-259.

Daniels, R.D. 1987. Saline seeps in the Northern Great Plains of the USA and the Southern Prairies of Canada. In: M. G. Wolman and F. G. A. Fournier, editors, Land Transformation in Agriculture. John Wiley & Sons Ltd.

DeSutter, T.M. 2008. Problems in production fields: Saline and sodic soils. In: S. L. e. al., editor Soil science: step-by-step field analysis. . Soil Science Society of America Special Publication, Madison, WI. p. 183-200.

Douaik, A., M. Van Meirvenne and T. Tóth. 2005. Soil salinity mapping using spatio-temporal kriging and Bayesian maximum entropy with interval soft data. Geoderma 128: 234-248.

Franzen, D. 2007. Managing Saline Soils in North Dakota. NDSU Extension Service. file:///C:/Users/Owner/Downloads/Saline%20and%20Sodic%20Soils%20%20(1).pdf (accessed 28 Dec. 2014).

Ganjegunte, G.K. and R.J. Braun. 2011. Delineating Salinity and Sodicity Distribution in Major Soil Map Units of El Paso, Texas, Using Electromagnetic Induction Technique. Soil Science 176: 441-447.

Geomatrix Earth Science Ltd. EM38-MK2. 2014. http://www.geomatrixsystems.com/. (accessed 28 Dec. 2014).

Guo, Y., Z. Shi, H.Y. Li and J. Triantafilis. 2013. Application of digital soil mapping methods for identifying salinity management classes based on a study on coastal central China. Soil Use and Management 29: 445-456.

He, Y., T. DeSutter, D. Hopkins, X. Jia and D.A. Wysocki. 2013. Predicting ECe of the saturated paste extract from value of EC1:5. Canadian Journal of Soil Science 93: 585-594.

Hogg, T.J. and J.L. Henry. 1984. Comparison of 1:1 and 1:2 suspensions and extracts with saturation extract in estimating salinity in Saskatchewan soils. Canadian Journal of Soil Science 64: 699-704.

Khorsandi, F. and F.A. Yazdi. 2011. Estimation of Saturated Paste Extracts' Electrical Conductivity from 1:5 Soil/Water Suspension and Gypsum. Communications in Soil Science and Plant Analysis 42: 315-321.

Li, H.Y., Z. Shi, R. Webster and J. Triantafilis. 2013. Mapping the three-dimensional variation of soil salinity in a rice-paddy soil. Geoderma 195-196: 31-41.

Li, H.Y., R. Webster and Z. Shi. 2015. Mapping soil salinity in the Yangtze delta: REML and universal kriging (E-BLUP) revisited. Geoderma 237-238: 71-77.

NRCS. 2014. Major Land Resource Areas Explorer. USDA-NRCS, http://apps.cei.psu.edu/mlra/ (accessed 01 Dec. 2014).

Provin, T. and J.L. Pitt. 2012. Managing Soil Salinity. Texas A&M Agrilife Extension Service E-60. http://soiltesting.tamu.edu/publications/E-60.pdf. (accessed 28 Dec. 2014).

Rhoades, J.D. 1982. Soluble Salts. Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties. ASA-SSSA, Madison, WI.

Rhoades, J.D., S.M. Lesch, P.J. Shouse and W.J. Alves. 1990. Locating Sampling Sites for Salinity Mapping. Soil Sci. Soc. Am. J. 54: 1799-1803.

Slavich, P. and G. Petterson. 1993. Estimating the electrical conductivity of saturated paste extracts from 1:5 soil, water suspensions and texture. Soil Research 31: 73-81.

Sonmez, S., D. Buyuktas, F. Okturen and S. Citak. 2008. Assessment of different soil to water ratios (1:1, 1:2.5, 1:5) in soil salinity studies. Geoderma 144: 361-369.

Sudduth, K.A., N.R. Kitchen, W.J. Wiebold, W.D. Batchelor, G.A. Bollero, D.G. Bullock, et al. 2005. Relating apparent electrical conductivity to soil properties across the north-central USA. Computers and Electronics in Agriculture 46: 263-283.

Taghizadeh-Mehrjardi, R., B. Minasny, F. Sarmadian and B.P. Malone. 2014. Digital mapping of soil salinity in Ardakan region, central Iran. Geoderma 213: 15-28.

US Salinity Laboratory Staff. 1954. Diagnosis and Improvement of Saline and Alkali Soils. In: L. Richards, editor Agricultural Handbook 60. USDA, Riverside, CA.

Vaughan, P.J., S.M. Lesch, D.L. Corwin, and D.G. Cone. 1995. Water Content Effect On Soil Salinity Prediction: A Geostatistical Study Using Cokriging. Soil Science Society of America Journal 59: 1146-1156.

Veris Technologies. 2014. http://www.veristech.com/. (accessed 28 Dec. 2014).

Wilkerson, H., R.K. Owen, C. Reese, T. DeSutter, D.E. Clay, C.G. Carlson. Unpublished data. 2014. Determination of total salt content in relation to electrical conductivity in slightly saline soils. South Dakota State University.

Zhang, H., J.L. Schroder, J.J. Pittman, J.J. Wang and M.E. Payton. 2005. Soil Salinity Using Saturated Paste and 1:1 Soil to Water Extracts. Soil Science Society of America Journal 69: 1146.

CHAPTER 2

RELATIONSHIP BETWEEN ELECTRICAL CONDUCTIVITY (EC) AND TOTAL SOLUBLE CATION (TSC) CONCENTRATIONS IN SELECTED BLACK GLACIATED PLAINS (MLRA 55B AND 55C) SOILS

ABSTRACT

Electrical conductivity (EC) is an important index for assessing salt affected soils and can also be used to predict the total soluble cations (TSC) in soil, but the relationship developed by Rhoades (1982) of EC x 10 = TSC is not accurate for soils affected by groundwater salinity in the Northern Great Plains. Therefore, the objectives of this study were to establish linear models for EC and TSC using selected South Dakota (SD) and North Dakota (ND), USA soils. Soil samples (n = 1245) were collected from four sites in SD and ND and analyzed for EC and soluble sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}). TSC was the sum of soluble Na^+, Ca^{2+}, and Mg^{2+}. Results showed that the linear relationship between EC and TSC was TSC = 13.54 *EC – 0.29 (R^2 = 0.88), which held true over EC values 0-18 dS m^{-1} and on a field, state, and regional scale. By establishing an accurate relationship between EC and TSC in this region, soil testing laboratories, crop consultants, soil scientists, government agencies, and educators have a simple way to relate EC to TSC and can more efficiently assess salt affected soils.

INTRODUCTION

Globally, electrical conductivity (EC) is a common index in assessing soil salinity. The ability of a soil solution to conduct electricity is directly related to the total amount of soluble cations (TSC) and anions (TSA) contained in a solution. EC readings

can be affected by soil moisture content (Vaughan, 1995), texture (Sudduth, et al., 2005), and mineral composition (US Salinity Laboratory Staff, 1954). The EC has been used to estimate the total dissolved cations in the solution. In 1954, the US Salinity Laboratory established the relationship of approximately 10:1 for EC (dS m^{-1}) to TSC ($mmole_c$ L^{-1}) , and since, this ratio has been used to simplify other salinity calculations, especially those involving the relative proportions of monovalent and divalent cations in the soil, and can serve as a quick field scale assessment of salinity issues (Rhoades, 1982, US Salinity Laboratory Staff, 1954). The total dissolved cation value is used to calculate the sodium adsorption ration (SAR). SAR is calculated using Equation 2.1:

$$SAR = \frac{[Na^+]}{\left(\frac{[Ca^{2+}] + [Mg^{2+}]}{2}\right)^{1/2}} \quad (2.1)$$

where SAR is the sodium adsorption ratio, $[Na^+]$ is the concentration of soluble sodium, $[Ca^{2+}]$ is the concentration of soluble calcium, and $[Mg^{2+}]$ is the concentration of soluble magnesium. In this calculation, the EC×10 value is used to calculate the approximate amount of Ca^{2+} + Mg^{2+} + Na^+ contained in solution. The Ca^{2+} and Mg^{2+} is determined by subtracting Na^+ from the EC×10 value.

This approach is based on the salt affected soils in the 17 Western States and Hawaii (US Salinity Laboratory Staff, 1954). Some crucial differences exist between the soils studied by Rhoades (1982) and the US Salinity Laboratory Staff (1954) and the salt-affected soils in the Central and Southern Black Glaciated Plains in South Dakota and North Dakota, USA (MLRA Regions 55B and 55C [NRCS, 2014a]). One of the primary differences is the source of the salts. In the Northern Great Plains, salinity occurs due to

the subsurface transport of salts with capillary water to the surface soil, whereas in the arid and semi-arid regions of the west salts are provided with irrigation water. The soils of the Black Glaciated Plains were formed in till that overlays Cretaceous marine shale from a prehistoric ocean, so groundwater brings salts from the shale bedrock to the glaciated surface soils (Daniels, 1987). These critical differences suggest that salt identification criteria developed for surface irrigated agricultural systems might have limited applications for the Northern Great Plains. The objective of this study was to establish a relationship between EC and TSC that would fit soils throughout the Central and Southern Black Glaciated Plains of South Dakota and North Dakota.

In laboratory studies done in South Dakota, with soils affected by groundwater salinity, the 10:1 relationship between EC and TSC did not hold true (Wilkerson, et al., 2014). Studies done in Canada, where groundwater salinity is prevalent as well, have also found that the original relationship does not work and have created new models for relating EC and TSC (Chang, 1983).

There are two main reasons to establish a robust relationship between EC and TSC. First, indirect measurements of EC, such as electromagnetic induction with EM38 (Geomatrix Earth Science Ltd.) or Veris (Veris Technologies, 2014) technology, are quick ways to assess soil salinity on a field scale (Rhoades, 1982). Next, research institutions and soil testing laboratories can use the relationship between EC and TSC to estimate the sodium adsorption ratio (SAR).

MATERIALS AND METHODS

Sample collection and processing

Soil samples were collected from the Northern Great Plains, USA in Day and Spink Counties (n=447), South Dakota (lat. 44.9250° to 45.4751° N, long. 97.8359° to 98.4760° W, respectively) and Grand Forks and Richland Counties (n=798), North Dakota (lat. 46.2046° to 47.9680° N, long. 97.0110° to 97.5084° W, respectively). The sampling depths were 0-7.5, 7.5-15, 15-30, and 30-60 cm depths in South Dakota and 0-15, 15-30, and 30-60 cm depths in North Dakota. The soils used for this study were all formed in glacially deposited parent materials with textures ranging from silt loams to silty clays. Full detail on the USDA-NRCS taxonomic classifications can be found in Tables 2.1 to 2.4. Samples were dried to 40^{o}C, ground, passed through a 2 mm sieve, and stored in plastic bags.

Lab analysis for electrical conductivity (EC) and total soluble cations (TSC)

EC and TSC concentrations were determined from a saturated paste extract using methods described by the US Salinity Laboratory Staff (1954). To obtain the saturated extract, approximately 150 g of soil was mixed with ultra-pure water until sample was completely saturated. Saturated samples were left to equilibrate for at least 8 hours. Soil solution was extracted through vacuum filtration using a Büchner funnel apparatus. Extract samples were stored at 4^{o}C until analyzed. EC was determined using a conductivity probe (South Dakota – PC 2700, Oakton Instruments, Vernon Hills, IL; North Dakota – Sension 378, Hach Co., Loveland CO) (Rhoades, 1982). Cation

concentrations of Na^+, Ca^{2+}, and Mg^{2+} were measured using flame atomic adsorption spectrophotometry (200 A, Buck Scientific, Norwalk, CT) (Rhoades, 1982). Na^+ and Mg^{2+} samples were diluted using ultra-pure water and Ca^{2+} samples were diluted using a calcium suppressant solution (La_2O_3·HCl solution) (National Soil Survey Center, 1996). Resulting concentrations were converted from ppm to $mmole_c\ L^{-1}$. TSC concentrations were determined by summing Na^+, Ca^{2+}, and Mg^{2+} in $mmole_c\ L^{-1}$.

Statistical analysis

Linear regression analysis was completed using non-transformed data in SAS 9.3 (SAS Institute, 2011)(Code in Appendix II). Statistical significance was determined at p = 0.05 for all analyses. The linear relationships were calculated for the EC and TSC for the following scenarios:

A - all samples,

B - low EC samples (<4.0 dS m^{-1}),

C - high EC samples (4.0-18 dS m^{-1}),

D - South Dakota samples only,

E - North Dakota samples only,

F - Day County, South Dakota samples only, and

G - Spink County, South Dakota samples only;

using Equation 2.2.

$$TCS = EC * a + b \quad (2.2)$$

where TCS is the total soluble cation concentration (in $mmole_c\ L^{-1}$), EC is the electrical conductivity (in dS m^{-1}), *a* is the slope of the equation, and *b* is the intercept on the y-axis.

RESULTS

Soil test results for the three ranges of EC are shown in Table 2.5. For all ranges of EC, the median is less than the mean, and the skewness coefficients are positive. These results are expected due to the clustered nature of saline and sodic soils. Figures 2.1 to 2.3 show the relationships for all EC data, low EC data, and high EC data, respectively, with TSC. The linear regression equations between EC and TSC over all EC values, low EC values, and high EC values were y = 13.54x – 0.30 (R^2 = 0.88), y = 13.03x - 0.16 (R^2 = 0.52), and y = 12.85x + 5.45 (R^2 = 0.71), respectively. The slopes of these three relationships were not significantly different which shows that one linear model can be used over all EC values 0-18 dS m^{-1}.

Regional scale results are shown in Figures 2.1 to 2.3. Soil test results for EC and TSC for all samples tested from South Dakota (SD) and North Dakota (ND) are shown in Table 2.6. Figure 2.4 shows the relationship between TSC and EC for SD samples. The slope of the relationship indicates the multiplication factor one can use to predict the TSC based on the EC. The linear regression equation between EC and TSC is y = 13.85x + 1.34 (R^2 = 0.90) with a 95% confidence interval for the slope of 13.4 to 14.3.

The values for EC and TSC for soils tested from ND are also shown in Table 6. Figure 5 shows the relationship between TSC and EC for ND samples analyzed. The linear regression equation between EC and TSC values is y = 13.01x – 0.02 (R^2 = 0.86)

with a 95% confidence interval for the slope of 12.6 to 13.4. Based on these results, there is no significant difference in the relationship between EC and TSC for the soils sampled from SD and ND, and the state scale relationships are not different from the regional scale model.

Soil test results for EC and TSC for all samples in Day County, SD and Spink County, SD are shown in Table 2.6. Figure 2.6 shows the relationship between TSC and EC for tested Day County soil samples. The slope of the relationship indicates the multiplication factor used to determine the TSC based on the EC. The linear regression equation between EC and TSC is y = 14.72x + 0.82 (R^2 = 0.94) with a 95% confidence interval for the slope of 14.1 to 15.3.

The values for EC and TSC soil data for Spink County, SD are also listed in Table 2.6 and Figure 2.7 shows the relationship between TSC and EC for selected Spink County samples. The linear regression equation between EC and TSC values is y = 13.69x + 1.11 (R^2 = 0.88) with a 95% confidence interval for the slope of 13.1 to 14.3. Based on these results, there is no significant difference in the relationship between EC and TSC for Day and Spink County samples, and the field scale relationships are not different from regional scale model.

DISCUSSION

The US Salinity Laboratory Staff (1954), showed a strong linear relationship between soil EC to TSC (slope ≈ 10, intercept ≈ 0) (Rhoades, 1982), however, this slope is different than values observed in the Northern Great Plains. Establishing an accurate relationship between EC and TSC in this region has widespread benefits, primarily for

soil testing laboratories, crop consultants, soil scientists, government agencies, and educators. An effective model would be able to predict TSC over all ranges of EC and be applicable on a regional scale. This study looked at the relationship between EC and TSC over a wide range of EC values (0-18 dS m^{-1}), low EC values (0-4 dS m^{-1}), and high EC values (4-18 dS m^{-1}). All of the relationships independently were statistically significant, and breaking down the range of EC values into low and high EC values did not affect the relationship. These findings suggest that one linear model can be used to predict TSC over a wide range of EC values. This study also looked at the relationship between EC and TSC for three different spatial scales – regional (Northern Great Plains), state (South Dakota and North Dakota), and field (Day and Spink Counties, SD). All of the relationships independently were statistically significant, but none of the relationships were different from one another. These results would indicate that a single model can be applied in this region as an accurate estimate of TSC based on EC data.

Studies in Alberta, Canada, in soils affected by groundwater salinity, showed a non-linear model where $TSC = 10.61EC^{1.22}$ (Chang, 1983). This study found that the linear relationship was the best fit for the data over all ranges of EC. The best fit non-linear model for this data was a polynomial relationship, but this equation would not be simple to calculate and does not improve the coefficient of determination for the model (Figure 8). Figure 2.9 shows the actual TSC from the samples tested and the predicted TSC values using the linear model for all EC values in the Northern Great Plains region (TSC = 13.54*EC – 0.29). When the intercept is forced through zero, the slope is near 1 and $R^2 = 0.87$, indicating that the regional linear model is a good fit.

The linear relationship using EC to predict TSC for low EC ranges (0-4 dS m^{-1}) of y = 13.03x - 0.16 (R^2 = 0.52) agrees with concurrent research completed in South Dakota that shows a relationship of y = 13.2x – 0.64 (R^2 = 0.61) (Wilkerson, 2014). The 95% confidence interval for the slope of the low EC value regression curve ranged from 12.1 to 13.9, and for the intercept, 0 was within the confidence range, therefore, this model is a good fit for slightly saline soils affected by groundwater salinity in the Northern Great Plains.

CONCLUSIONS

The goal of this study was to establish a relationship between electrical conductivity (EC) and the total soluble cations (TSC) in order to reduce the soil analysis needed to diagnose saline and sodic soils. Specifically, if EC can accurately predict TSC, researchers and soil testing laboratories can calculate the sodium adsorption ratio (SAR) using only EC and Na^+, eliminating the need to analyze for Ca^{2+} and Mg^{2+} (see Equation 2.1). Previously developed models are not suited for soils affected by groundwater salinity in the Northern Great Plains, and a new, easy-to-use model is needed. Based on the results of this study, a linear model of TSC = 13.54*EC -0.29 is suited for the Northern Great Plains region over all values of EC and can be applied with accuracy to saturated paste extractions analyzed for EC.

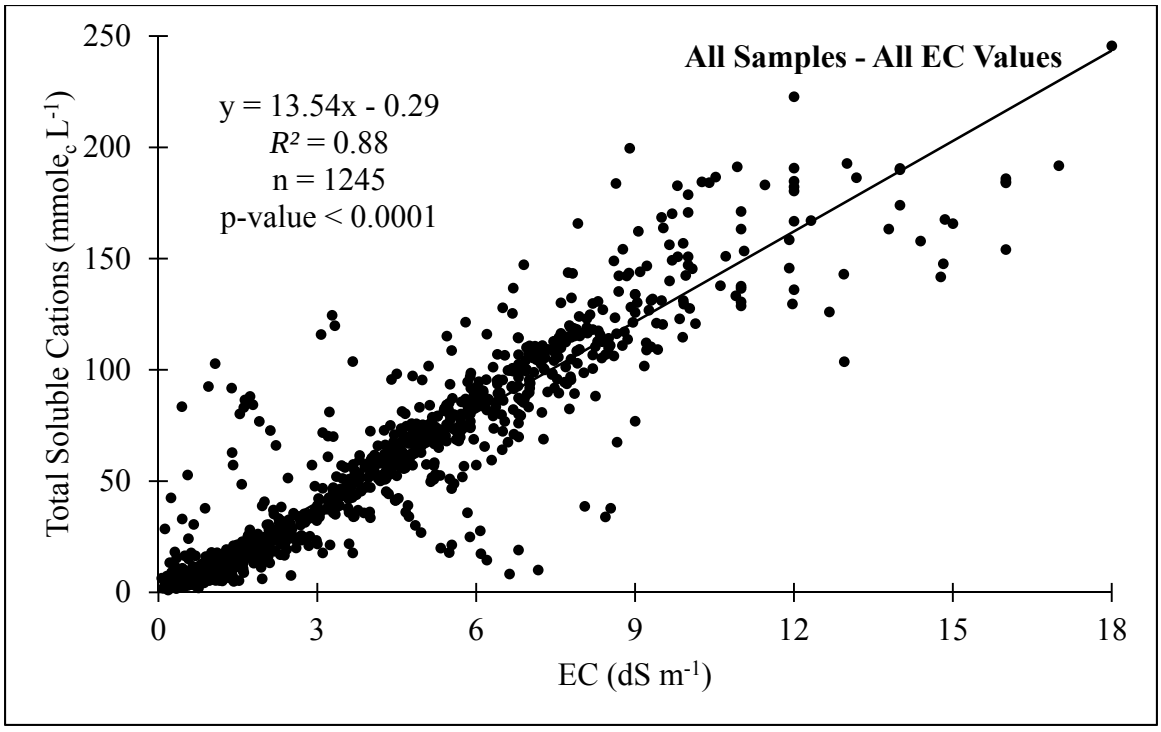

Figure 2.1. Regional trend for electrical conductivity (EC) and total soluble cation (TSC) concentrations for groundwater derived saline-sodic soil samples in South Dakota and North Dakota with EC values ranging from 0 to 18 dS m^{-1}. Dominant soils: Hapludolls, Natrudolls, Calciudolls, Argiudolls, Calciaquolls, Endoaquolls, Calciaquerts, Natraquerts, Natraquolls, and Argialbolls (Soil Survey Division, 2014).

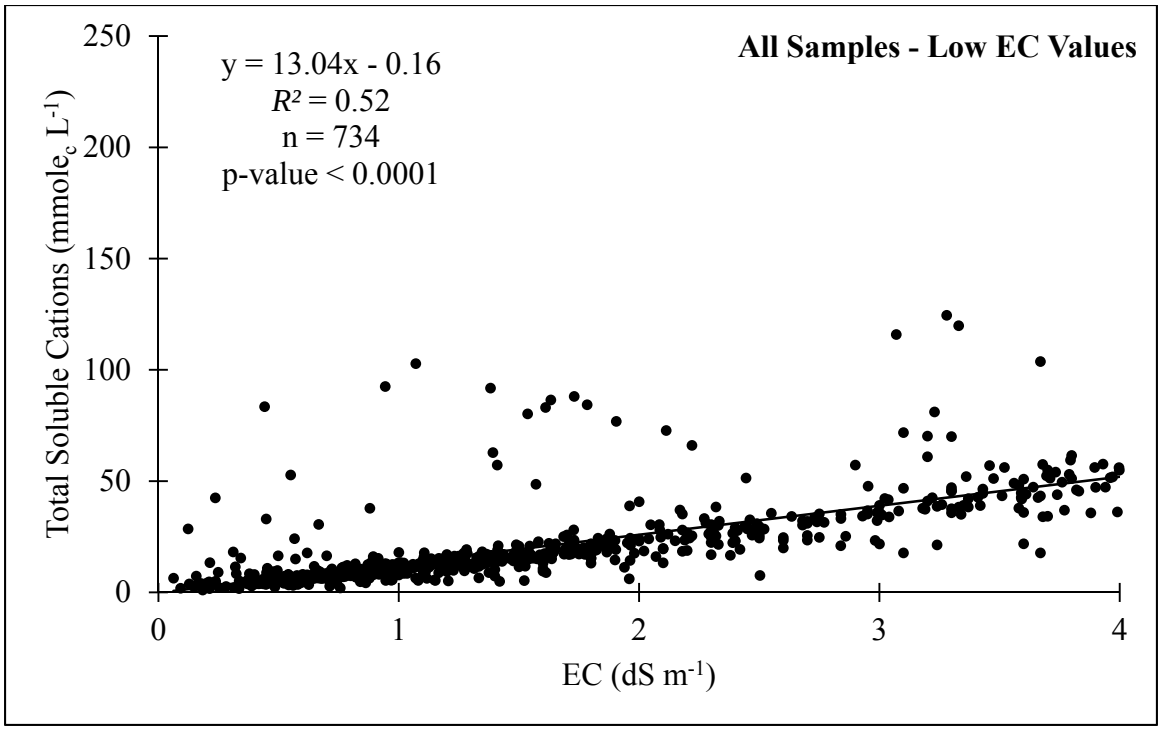

Figure 2.2. Regional trend for groundwater derived saline-sodic soil electrical conductivity (EC) and total soluble cation (TSC) concentrations for non-saline to slightly saline soil samples in South Dakota and North Dakota with EC values ranging from 0 to 4 dS m^{-1}. Dominant soils: Hapludolls, Natrudolls, Calciudolls, Argiudolls, Calciaquolls, Endoaquolls, Calciaquerts, Natraquerts, Natraquolls, and Argialbolls (Soil Survey Division, 2014).

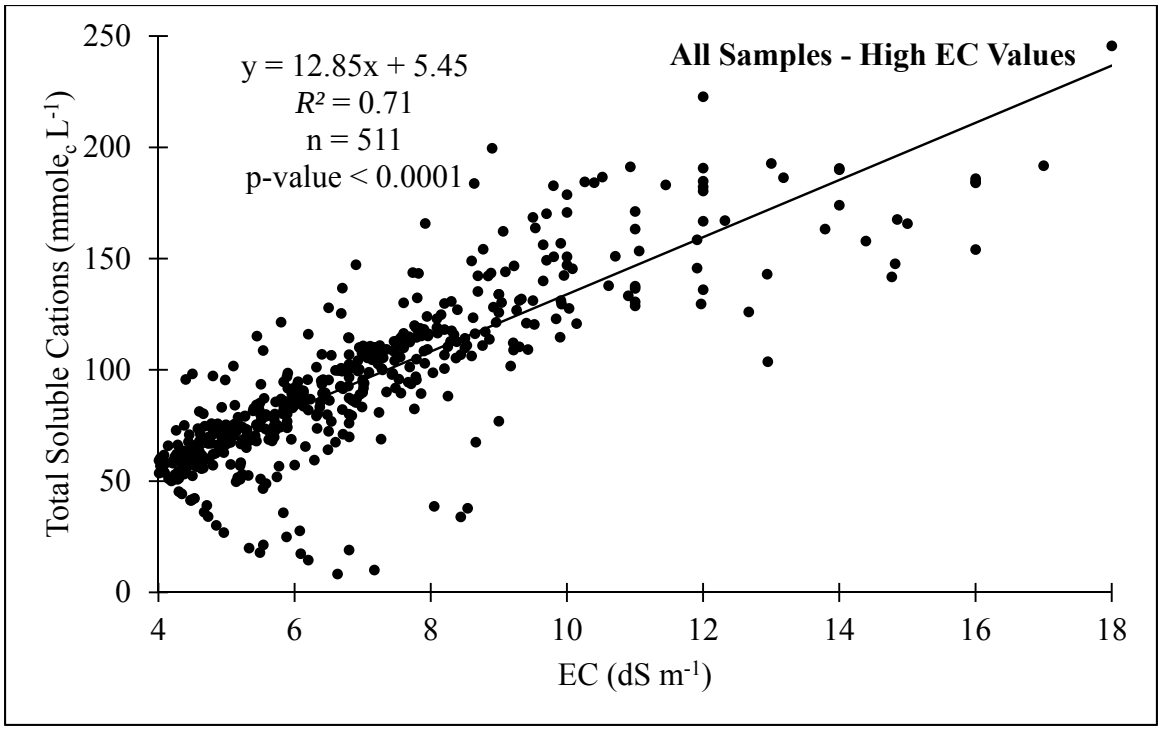

Figure 2.3. Regional trend for electrical conductivity (EC) and total soluble cation (TSC) concentrations for groundwater derived saline-sodic soil samples in South Dakota and North Dakota with EC values ranging from 4 to 18 dS m^{-1}. Dominant soils: Hapludolls, Natrudolls, Calciudolls, Argiudolls, Calciaquolls, Endoaquolls, Calciaquerts, Natraquerts, Natraquolls, and Argialbolls (Soil Survey Division, 2014).

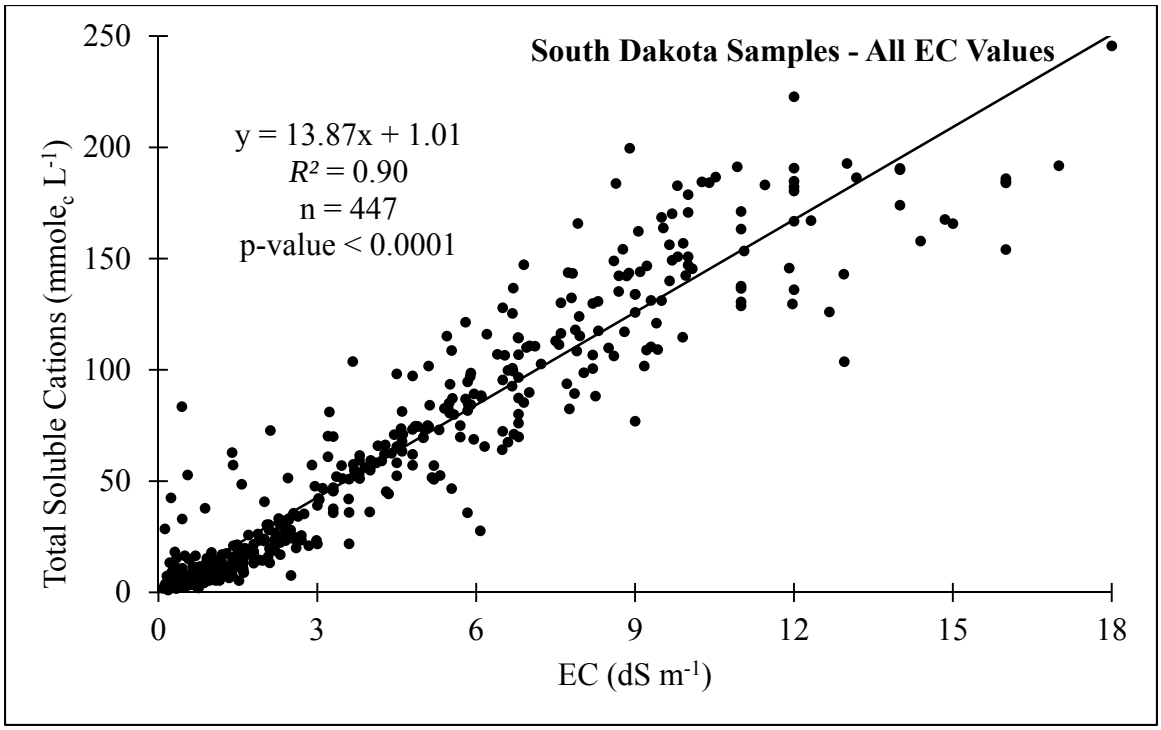

Figure 2.4. Statewide trend for electrical conductivity (EC) and total soluble cation (TSC) concentrations for groundwater derived saline-sodic soil samples in South Dakota with EC values ranging from 0 to 18 dS m^{-1}. Dominant soils: Hapludolls, Natrudolls, Calciudolls, Argiudolls, Calciaquolls, Endoaquolls, and Argialbolls (Soil Survey Division, 2014).

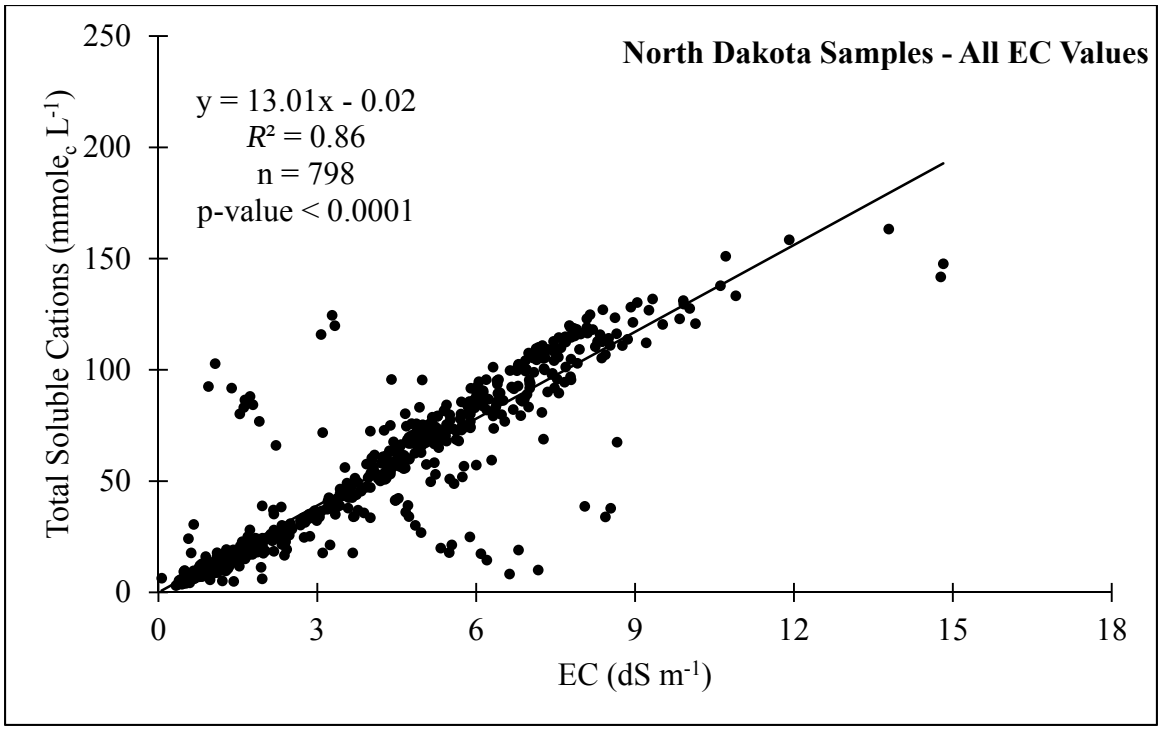

Figure 2.5. Statewide trend for electrical conductivity (EC) and total soluble cation (TSC) concentrations for groundwater derived saline-sodic soil samples in North Dakota with EC values ranging from 0 to 15 dS m^{-1}. Dominant soils: Natrudolls, Endoaquolls, Calciaquerts, Natraquerts, Natraquolls, and Calciaquolls.

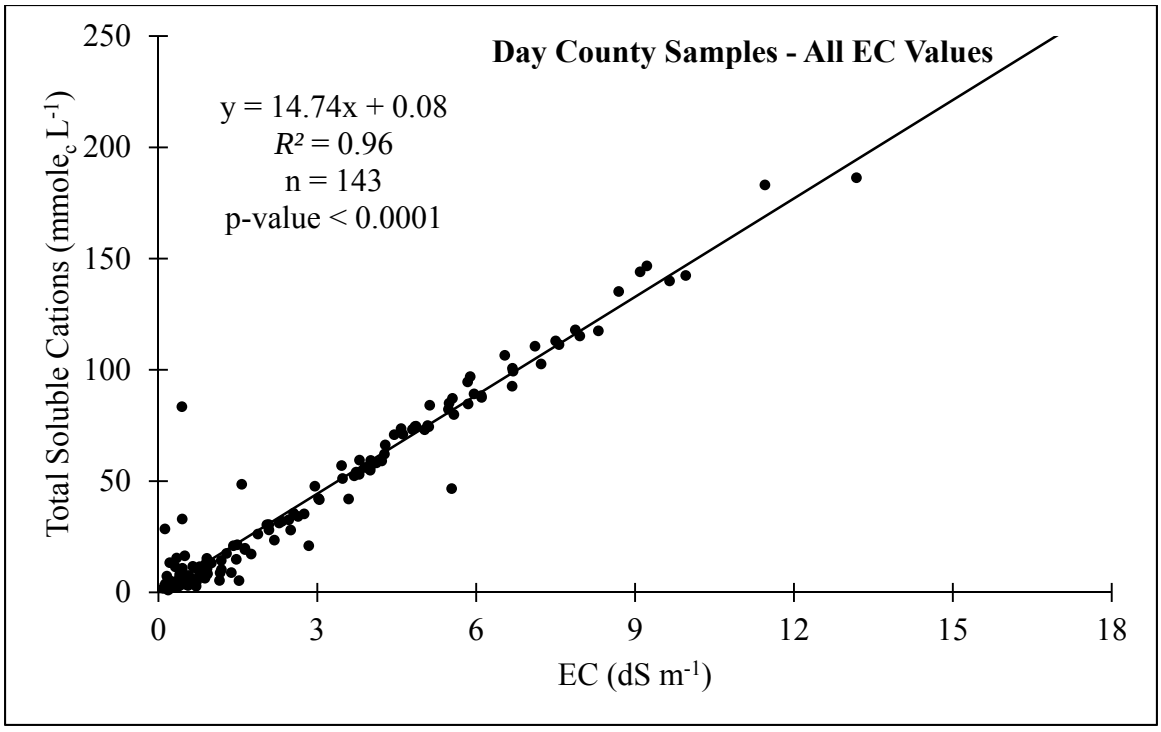

Figure 2.6. Field-scale trend for electrical conductivity (EC) and total soluble cation (TSC) concentrations for groundwater derived saline-sodic soil samples in Day County*, South Dakota with EC values ranging from 0 to 18 dS m^{-1}.
*45.4751° N, 97.8359° W (Dominant soils: Hapludolls, Natrudolls, Calciudolls, Argiudolls, Calciaquolls, and Endoaquolls [Soil Survey Division, 2014])

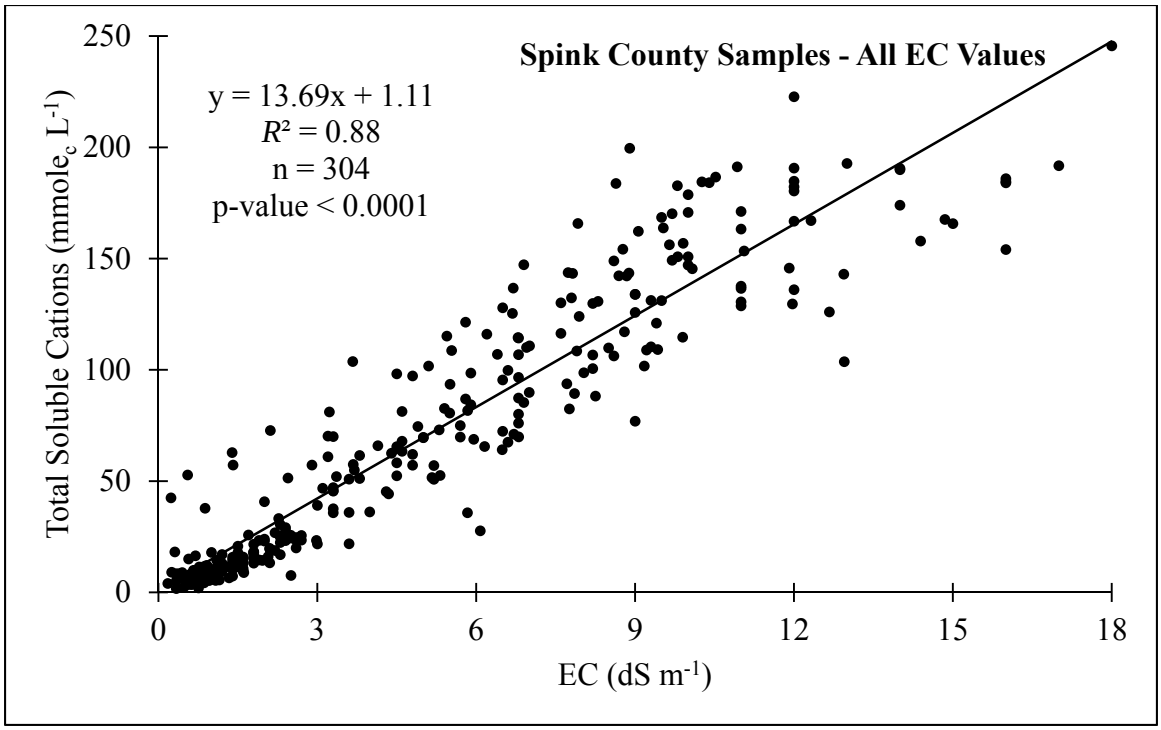

Figure 2.7. Field-scale trend for electrical conductivity (EC) and total soluble cation (TSC) concentrations for groundwater derived saline-sodic soil samples in Spink County*, South Dakota with EC values ranging from 0 to 18 dS m^{-1}.
*44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Natrudolls, Argiudolls, Argialbolls [Soil Survey Division, 2014])

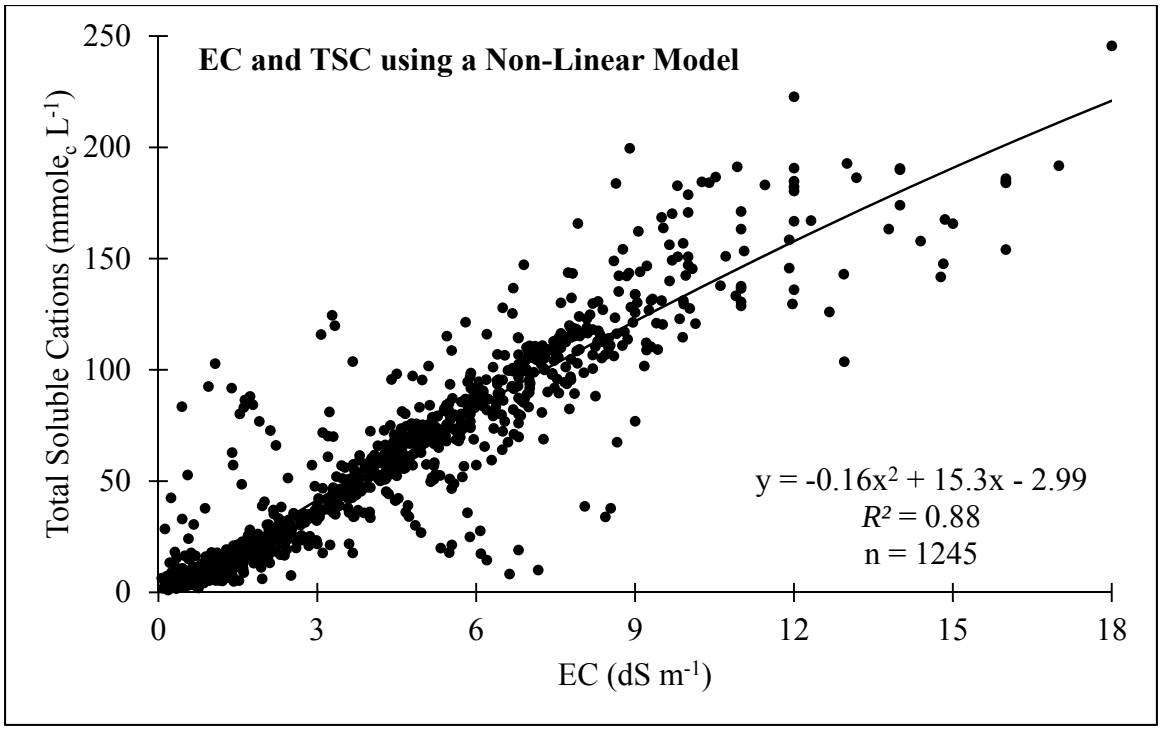

Figure 2.8. Regional trend for electrical conductivity (EC) and total soluble cation (TSC) concentrations for groundwater derived saline-sodic soil samples in South Dakota and North Dakota with EC values ranging from 0 to 18 dS m^{-1}, fit with a non-linear trend line. Dominant soils: Hapludolls, Natrudolls, Calciudolls, Argiudolls, Calciaquolls, Endoaquolls, Calciaquerts, Natraquerts, Natraquolls, and Argialbolls (Soil Survey Division, 2014).

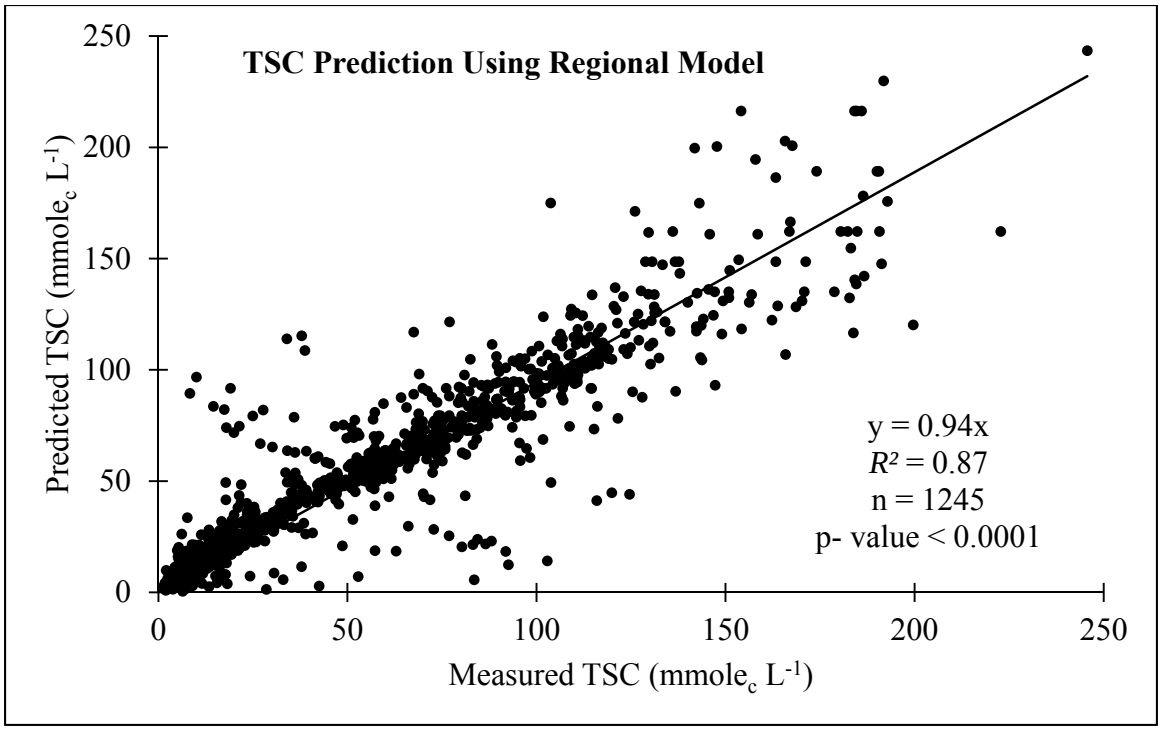

Figure 2.9. Regional trend for measured and predicted total soluble cation (TSC) concentrations for groundwater derived saline-sodic soil samples in South Dakota and North Dakota with EC values ranging from 0 to 18 dS m^{-1}. Dominant soils: Hapludolls, Natrudolls, Calciudolls, Argiudolls, Calciaquolls, Endoaquolls, Calciaquerts, Natraquerts, Natraquolls, and Argialbolls (Soil Survey Division, 2014).

Table 2.1. Soil classification, slope, and parent material information for Day County, South Dakota soil samples. Samples were collected near Pierpont*, South Dakota in November 2013 following soybean (*Glycine max* L.) harvest.

Map Unit Symbol	Series**	Slope (%)	Taxonomic Classification***	Parent Material
G102A	Hamerly loam	0-3	Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls	Fine-loamy till
G190C	Forman-Buse-Aastad loams	3-9	Fine-loamy, mixed, superactive, frigid Calcic Argiudolls Fine-loamy, mixed, superactive, frigid Typic Calciudolls Fine-loamy, mixed, superactive, frigid Pachic Argiudolls	Fine-loamy till
G543A	Playmoor silty clay loam	0-2	Fine-silty, mixed, superactive, calcareous, frigid Cumulic Endoaquolls	Silty alluvium
G790A	Kranzburg-Brookings silt loams	0-2	Fine-silty, mixed, superactive, frigid Calcic Hapludolls Fine-silty, mixed, superactive, frigid Pachic Hapludolls	Silty loess over fine-loamy till
G790B	Kranzburg-Brookings silt loams	2-6	Fine-silty, mixed, superactive, frigid Calcic Hapludolls Fine-silty, mixed, superactive, frigid Pachic Hapludolls	Silty loess over fine-loamy till
G792B	Kranzburg-Brookings-Buse complex	0-6	Fine-silty, mixed, superactive, frigid Calcic Hapludolls Fine-silty, mixed, superactive, frigid Pachic Hapludolls Fine-loamy, mixed, superactive, frigid Typic Calciudolls	Silty loess over fine-loamy till
G852A	Nahon-Aberdeen-Exline silt loams	0-2	Fine, smectitic, frigid Calcic Natrudolls Fine, smectitic, frigid Glossic Natrudolls Fine, smectitic, frigid Leptic Natrudolls	Silty and clayey glaciolacustrine deposits over fine-loamy till
G862A	Harmony-Beotia silt loams	0-2	Fine, smectitic, frigid Pachic Argiudolls Fine-silty, mixed, superactive, frigid Pachic Hapludolls	Silty and clayey glaciolacustrine deposits

*45.4751° N, 97.8359° W
**(NRCS, 2014b)
***(Soil Survey Division, 2014)

Table 2.2. Soil classification, slope, and parent material information for Spink County, South Dakota soil samples. Samples were collected near Redfield*, South Dakota in June and July 2013 following corn (*Zea mays* L.) planting.

Map Unit Symbol	Series**	Slope (%)	Taxonomic Classification***	Parent Material
G720A	Great Bend-Beotia silt loams	0-2	Fine-silty, mixed, superactive, frigid Calcic Hapludolls Fine-silty, mixed, superactive, frigid Pachic Hapludolls	Fine-silty glaciolacustrine deposits
G722B	Great Bend-Zell silt loams	2-6	Fine-silty, mixed, superactive, frigid Calcic Hapludolls Coarse-silty, mixed, superactive frigid Typic Calciudolls	Fine-silty glaciolacustrine deposits
G866A	Harmony-Aberdeen silty clay loams	0-2	Fine, smectitic, frigid Pachic Argiudolls Fine, smectitic, frigid Glossic Natrudolls	Silty and clayey glaciolacustrine deposits
G868A	Winship-Tonka silt loams	0-1	Fine-silty, mixed, superactive, frigid Pachic Argiudolls Fine, smectitic, frigid Argiaquic Argialbolls	Fine silty-glaciolacustrine deposits

*44.9250° N, 97.4760° W
**(NRCS, 2014b)
***(Soil Survey Division, 2014)

Table 2.3. Soil classification, topographic, and parent material information for Grand Forks County, North Dakota soil samples.

Map Unit Symbol	Series**	Slope (%)	Taxonomic Classification***	Parent Material
I119A	Bearden silty clay loams	0-1	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls	Calcareous silt loam and silty clay loam lacustrine sediments
I176A	Ojata silty clay loams	0-1	Fine-silty, mixed, superactive, frigid Typic Calciaquolls	Calcareous, silty lake sediments
I376A	Colvin silty clay loams	0-1	Fine-silty, mixed, superactive, frigid Typic Calciaquolls	Silt loam and silty clay loam sediments
I601A	Bearden silty clay loams, saline	0-1	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls	Calcareous silt loam and silty clay loam lacustrine sediments

*47.9330° N, 97.1736° W
**(NRCS, 2014b)
***(Soil Survey Division, 2014)

Table 2.4. Soil classification, topographic, and parent material information for Richland County, North Dakota soil samples.

Map Unit Symbol	Series**	Slope (%)	Taxonomic Classification***	Parent Material
I253A	Exline sand substratum	0-1	Fine, smectitic, frigid Leptic Natrudolls	Lacustrine and alluvial deposits
I259A	McDonaldsville silty clay	0-1	Clayey over sandy or sandy-skeletal, smectitic over mixed, frigid Vertic Endoaquolls	Clayey and sandy glaciolacustrine sediments
I261A	McDonaldsville-Hegne sandy substratum silty clays	0-1	Clayey over sandy or sandy-skeletal, smectitic over mixed, frigid Vertic Endoaquolls	Clayey and sandy glaciolacustrine sediments
			Fine, smectitic, frigid Typic Calciaquerts	Clayey calcareous lacustrine sediments
I262A	McDonaldsville-Ryan sandy substratum silty clays	0-1	Clayey over sandy or sandy-skeletal, smectitic over mixed, frigid Vertic Endoaquolls	Clayey and sandy glaciolacustrine sediments
			Fine, smectitic, frigid Typic Natraquerts	Alkaline clayey sediments
I313A	Stirum-Arveson loams	0-1	Coarse-loamy, mixed, superactive, frigid Typic Natraquolls	Glaciofluvial deposits, glaciolacustrine deposits, or alluvium
			Coarse-loamy, mixed, superactive, frigid Typic Calciaquolls	Loamy glaciolacustrine or outwash sediments

*46.2823° N, 97.2594° W
**(NRCS, 2014b)
***(Soil Survey Division, 2014)

Table 2.5. Soil test data for electrical conductivity (EC) and total soluble cations (TSC) for all samples studied. The samples are sorted by EC range. Low EC values (0-4 dS m^{-1}) represent non-saline to slightly saline soils; High EC values (4-18 dS m^{-1}) represent moderately saline to highly saline soils; and All EC values represent all soils from the study.

EC Range	n	Statistics	EC (dS m^{-1})	TSC ($mmole_c$ L^{-1})
Low EC	734	mean	1.47	19.1
		st.dev	±0.97	±17.5
		median	1.17	13.1
		range	0.06 – 4.00	1.09 – 125
		skewness*	0.98	2.40
		kurtosis**	-0.00	7.52
High EC	511	mean	6.98	95.1
		st.dev	±2.47	±37.7
		median	6.48	89.1
		range	4.01 – 18.0	8.32 – 246
		skewness	1.46	0.74
		kurtosis	2.56	0.63
All EC values	1245	mean	3.73	50.3
		st.dev	±3.22	±46.5
		median	2.66	32.3
		range	0.06 – 18.0	1.09 – 246
		skewness	1.12	1.04
		kurtosis	1.03	0.40

***** Skewness describes data deviation left or right of the mean from a normal distribution
**Kurtosis describes the peakedness or flatness of the data
Dominant soils: Hapludolls, Natrudolls, Calciudolls, Argiudolls, Calciaquolls, Endoaquolls, Calciaquerts, Natraquerts, Natraquolls, and Argialbolls (Soil Survey Division, 2014)

Table 2.6. Soil test data for electrical conductivity (EC) and total soluble cations (TSC) for all study samples. Samples are sorted by location and sampling scale. Day County, SD and Spink County, SD are field-scale samples; All SD and All ND are state-scale samples; and All Sites includes the regional-scale sampling in the Northern Great Plains.

Location	n	Statistics	EC ($dS\ m^{-1}$)	TSC ($mmole_c\ L^{-1}$)
Day County, SD†	143	mean	3.04	45.0
		st.dev	±3.40	±51.0
		median	1.75	28.0
		range	0.09 – 18.0	1.09 – 379
		skewness*	2.68	2.56
		kurtosis**	13.3	12.1
Spink County, SD‡	304	mean	5.14	71.4
		st.dev	±4.13	±60.4
		median	4.22	57.4
		range	0.18 – 18.0	1.73 – 246
		skewness	0.78	0.60
		kurtosis	-0.24	-0.86
All SD	447	mean	4.46	63.0
		st.dev	±4.02	±58.8
		median	3.30	46.8
		range	0.09 – 18.0	1.09 – 379
		skewness	1.18	1.05
		kurtosis	1.59	1.10
All ND	798	mean	3.35	43.5
		st.dev	±2.69	±37.8
		median	2.33	26.3
		range	0.06 – 14.8	3.09 – 163
		skewness	0.86	0.78
		kurtosis	0.14	-0.62
All Sites	1245	mean	3.73	50.3
		st.dev	±3.22	±46.5
		median	2.66	32.3
		range	0.06 – 18.0	1.09 – 246
		skewness	1.12	1.04
		kurtosis	1.03	0.40

†45.4751° N, 97.8359° W (Dominant soils: Hapludolls, Natrudolls, Calciudolls, Argiudolls, Calciaquolls, and Endoaquolls [Soil Survey Division, 2014])
‡44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Natrudolls, Argiudolls, Argialbolls [Soil Survey Division, 2014])
* Skewness describes data deviation left or right of the mean from a normal distribution
**Kurtosis describes the peakedness or flatness of the data

REFERENCES

Chang, C., T.G. Sommerfeldt, J.M. Carefoot, and G.B. Schaalje. 1983. Relationships of electrical conductivity with total dissolved salts and cation concentration of sulfate-dominant soil extracts. Canadian Journal of Soil Science 63: 79-86.

Daniels, R.D. 1987. Saline seeps in the Northern Great Plains of the USA and the Southern Prairies of Canada. In: M. G. Wolman and F. G. A. Fournier, editors, Land Transformation in Agriculture. John Wiley & Sons Ltd.

Geomatrix Earth Science Ltd. EM38-MK2. http://www.geomatrixsystems.com/. (accessed 28 Dec. 2014).

National Soil Survey Center. 1996. Soil Survey Methods Laboratory Manual USDA-NRCS.

NRCS. 2014a. Major Land Resource Area Explorer. USDA-NRCS, http://apps.cei.psu.edu/mlra/ (accessed 01 Dec. 2014).

NRCS. 2014b. Web Soil Survey. USDA-NRCS, http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx (accessed 01 Dec. 2014).

Rhoades, J.D. 1982. Soluble Salts. Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties. ASA-SSSA, Madison, WI.

SAS Institute. 2011. SAS® 9.3 SQL Procedure User's Guide.

Soil Survey Division. 2014. Official Soil Series Descriptions. USDA-NRCS, https://soilseries.sc.egov.usda.gov/osdname.asp (accessed 01 Dec. 2014)

Sudduth, K.A., N.R. Kitchen, W.J. Wiebold, W.D. Batchelor, G.A. Bollero, D.G. Bullock, et al. 2005. Relating apparent electrical conductivity to soil properties across the north-central USA. Computers and Electronics in Agriculture 46: 263-283.

US Salinity Laboratory Staff. 1954. Diagnosis and Improvement of Saline and Alkali Soils. In: L. Richards, editor Agricultural Handbook 60. USDA, Riverside, CA.

Vaughan, P.J., S.M. Lesch, D.L. Corwin, and D.G. Cone. 1995. Water Content Effect On Soil Salinity Prediction: A Geostatistical Study Using Cokriging. Soil Science Society of America Journal 59: 1146-1156.

Veris Technologies. 2014. http://www.veristech.com/. (accessed 28 Dec. 2014).

Wilkerson, H., R.K. Owen, C. Reese, T. DeSutter, D.E. Clay, C.G. Carlson. Unpublished data. 2014. Determination of total salt content in relation to electrical conductivity in slightly saline soils. South Dakota State University.

CHAPTER 3

THE EFFECT OF SOIL:WATER SOLUTION RATIOS ON THE ELECTRICAL CONDUCTIVITY (EC) AND SODIUM ADSORPTION RATIO (SAR) IN SELECTED SOUTHERN BLACK GLACIATED PLAINS (MLRA 55C) SOILS

ABSTRACT

Traditionally, electrical conductivity (EC) and sodium adsorption ratio (SAR) have been measured using saturated paste extraction methods, but this procedure can be time consuming and tedious. Due to the time limitations, many soil testing labs are using simplified 1:1 and 1:5 soil:water dilution extraction methods to analyze soil EC and sodium (Na^+) content. The objective of this study was to determine the relationship between EC, Na^+, calcium (Ca^{2+}), magnesium (Mg^{2+}), and SAR measured using saturated paste extraction methods, and 1:1 and 1:5 soil:water dilution extraction methods. Based on the results of this study, not only can linear regression relationships be developed between saturated paste extractions and various soil:water dilutions, but a non-linear relationship can also be established to predict the salinity parameters based on the dilution factor. Using this non-linear relationship for EC, Na^+, Ca^{2+}, Mg^{2+}, or SAR would allow any dilution results to be converted to any other dilution (within the range of dilutions studied), including a saturated paste extraction.

INTRODUCTION

Salt affected soils are a major limitation to crop production in the Northern Great Plains and worldwide (Franzen, 2007). Producers must be able to understand the saline and sodic soil problems in their fields in order to make proper management decisions, such as crop selection, amendment application (for sodic and saline-sodic soils), and water management. Crop selections are based on salt-tolerance recommendations and perennial vegetation can be used to reclaim salt affected soils (Franzen, 2007). Chemical amendments, such as gypsum, may be needed to replace sodium (Na^+) on the cation exchange capacity (CEC) sites and leach excess Na^+ (DeSutter, 2008). In the Northern Great Plains, salt affected soils are often the result of salty groundwater near the soil surface (Franzen, 2007), so subsurface drainage may also be considered to manage salt affected soils (US Salinity Laboratory Staff, 1954). Research and extension publications typically make recommendations for salt-affected soil management using electrical conductivity (EC) and sodium adsorption ratio (SAR).

Traditionally, EC and SAR have been measured using saturated paste extraction methods (Rhoades, 1982, US Salinity Laboratory Staff, 1954), but this procedure can be time consuming and tedious. Due to the time limitations, many soil testing labs are using simplified methods to analyze soil EC and Na+ content. Survey results of soil testing labs in Fall 2013 (Appendix I) showed that most labs use a 1:1 soil:water (w/w) dilution extraction (Rhoades, 1982) to measure EC and report Na^+ content as the percent Na^+ of the base saturation, determined using an ammonium acetate extraction method (Chapman, 1965). These different procedures cause discrepancies between values

reported from research and extension publications and the soil testing results, which can cause confusion for producers and natural resource managers.

Extensive research has been done to establish the relationship between EC determined from saturated paste extractions (EC_e) and EC determined from soil:water dilutions ($EC_{1:1}$, $EC_{1:2}$, $EC_{1:2.5}$, $EC_{1:5}$). Franzen (2007) found the relationship for medium textured soils in North Dakota, USA to be $EC_e = 3.01EC_{1:1} - 0.77$. Hogg and Henry (1984), found the regression equations between methods to be $EC_e = 1.62EC_{1:1} - 0.24$ and $EC_e = 2.35EC_{1:2} - 0.36$ for medium textured soils in Saskatchewan, Canada. In Oklahoma, USA, Zhang, et al. (2005) determined that the regression model for predicting EC_e was $EC_e = 1.85EC_{1:1}$ when the intercept is forced through 0. Khorsandi and Yazdi (2011) found a relationship of $EC_e = 5.60EC_{1:5} - 4.37$ for soils with gypsum in the Yazd Province of Iran. He, et al. (2013) found that $EC_e = 2.74EC_{1:5} + 3.01$ in North Dakota, USA. Slavich and Petterson (1993) concluded that the best fit model for soils in the Riverine Plain, Australia was $EC_e = fEC_{1:5}$ where $f = 2.46 + 3.03/\theta SP$ and θSP indicates the water content of the saturated paste extraction. Finally, Sonmez, et al. (2008) looked at several different soil:water dilutions in Antalya, Turkey and found the following models were best suited in medium textured soils: $EC_e = 2.15EC_{1:1} - 0.44$, $EC_e = 3.84EC_{1:2.5} + 0.35$, and $EC_e = 7.58EC_{1:5} + 0.06$.

While many relationships have been found to predict EC_e using various soil:water dilutions, the results are not consistent, indicating regional variability. Also, little work has been done to measure soluble cations and predict Na^+ content with different soil:water dilutions. Sonmez, et al. (2008) outlined the models that have been established for soluble cation concentrations. For linear regression, the slopes of these models ranged

from 0.95 to 2.78 for Na^+, 0.7 to 2.25 for Ca^{2+}, and 0.7 to 1.75 for Mg^{2+} when predicting the saturated paste extraction concentration using a 1:1 soil:water extraction concentration. A model predicting SAR_e would be proportional to the soluble cation concentration models, and would allow soil testing laboratories to report the soil sodium content in a format that producers could interpret and apply to their management practices.

Based on past research and current demands for salt affected soil management in the Northern Great Plains, the primary objective of this study was to determine the relationship between EC, Na^+, Ca^{2+}, Mg^{2+}, and SAR measured using saturated paste extraction methods, and 1:1 and 1:5 soil:water dilution extraction methods. The resulting models will be used to close the gap between research institutions and soil testing laboratories, and help producers better manage saline and sodic soils for production agriculture.

MATERIALS AND METHODS

Sample collection and processing

Soil samples were collected from the Northern Great Plains, USA (MLRA 55C – Southern Black Glaciated Plains [NRCS, 2014a]) in Spink County South Dakota (lat. 44.9710° N, long. 98.4675° W). The sampling depths were 0-7.5, 7.5-15, and 15-30 cm. The soils used for this study were all formed in glacially deposited parent materials. Full detail on the USDA taxonomic classifications can be found in Table 3.1. Samples were collected in June 2013 along four transects, with points every 10 m. Samples were air dried to 40^{o}C, ground, passed through a 2 mm sieve, and stored in plastic bags.

Lab analysis for electrical conductivity (EC), soluble cations, and sodium adsorption ratio (SAR)

Soil EC and soluble cation concentrations were determined using three selected soil:water solution ratios:

A. a saturated extract;

B. a soil to water ratio of 1:1; and

C. a soil to water ratio of 1:5 using methods described by Rhoades (1982).

To obtain the saturated extract, approximately 150 g of soil was mixed with ultra-pure water until sample was completely saturated. Saturated samples were left to equilibrate for at least 8 hours. Soil solution was extracted through vacuum filtration using a Büchner funnel apparatus. Extract samples were stored at 4°C until analyzed. For the 1:1 and 1:5 soil to water ratio extraction, 50 g and 10 g of soil, respectively, were mixed with 50 mL of ultra-pure water and shaken for 30 minutes. The resulting solution was decanted from plastic containers after equilibrating for at least 30 minutes. EC was determined using a conductivity probe (South Dakota – PC 2700, Oakton Instruments, Vernon Hills, IL; North Dakota – Sension 378, Hach Co., Loveland CO) (Rhoades, 1982). Cation concentrations of Na^+, Ca^{2+}, and Mg^{2+} were measured using flame atomic adsorption spectrophotometry (200 A, Buck Scientific, Norwalk, CT) (Rhoades, 1982). Na^+ and Mg^{2+} samples were diluted using ultra-pure water and Ca^{2+} samples were diluted using a calcium suppressant solution ($La_2O_3 \cdot HCl$ solution) (National Soil Survey Center, 1996). Resulting concentrations were converted from ppm to $mmole_c\ L^{-1}$. Sodium adsorption ratio (SAR) was calculated using Equation 3.1.

$$SAR = \frac{[Na^+]}{\left(\frac{[Ca^{2+}] + [Mg^{2+}]}{2}\right)^{1/2}} \quad (3.1)$$

Throughout this manuscript, parameters measured using saturated paste extractions will be designated with a subscript 'e' (EC_e, Na^+_e, Ca^{2+}_e, Mg^{2+}_e, SAR_e). All parameters measured using a 1:1 soil:water dilution extraction will be designated with a subscript '1:1' ($EC_{1:1}$, $Na^+_{1:1}$, $Ca^{2+}_{1:1}$, $Mg^{2+}_{1:1}$, $SAR_{1:1}$). Finally, all parameters measured using a 1:5 soil:water dilution extraction will be designated with a subscript '1:5' ($EC_{1:5}$, $Na^+_{1:5}$, $Ca^{2+}_{1:5}$, $Mg^{2+}_{1:5}$, $SAR_{1:5}$).

Statistical analysis

Regression analysis was completed using non-transformed data in SAS 9.3 (SAS Institute, 2011)(Code in Appendix II). Statistical significance was determined at $p = 0.05$ for all analyses. Linear relationships were determined for saturated paste EC, Na^+, Ca^{2+}, Mg^{2+}, and SAR with 1:1 soil to water dilutions and 1:5 soil to water dilutions for those same parameters. The dilution factors of each test and their respective mean, standard deviation, and linear regression slope for each parameter were analyzed with non-linear regression.

RESULTS

Characterization of dilution relationship for electrical conductivity (EC)

Soil test results for EC are shown in Table 3.2. The least dilute extraction, approximately 1:0.5 for EC_e, produced the highest test values, whereas the most dilute,

$EC_{1:5}$, produced the lowest test values, however, none of the dilutions produced significantly different results at $\alpha = 0.05$. Differences in the soil test values between dilutions did result in dissimilarities in the characterization curves that compared $EC_{1:1}$ and $EC_{1:5}$ dilutions with EC_e, and $EC_{1:1}$ with $EC_{1:5}$.

Figure 3.1 shows the relationship for EC_e with $EC_{1:1}$ and $EC_{1:5}$, $EC_{1:1}$ with $EC_{1:5}$, and the soil:water dilution factor with the means of each test. If all testing methods produce equivalent results, the slope of the regression line between $EC_{1:1}$ and EC_e and $EC_{1:5}$ and EC_e will be 1 and the slope of the regression line comparing the soil:water dilution factor with the means of each test would be 0. If the relationship between testing methods was solely based on the dilution, the slope between $EC_{1:1}$ and EC_e would be approximately 2, the slope between $EC_{1:5}$ and EC_e would be approximately 10, and the relationship for the regression line comparing the soil:water dilution factor with the means of each test would be linear. These relationships would be true for all other parameters as well.

The linear regression equations for EC are shown in Figure 3.1, a-c. All three relationships are statistically significant with p-values < 0.01. The slope for the regression equation between EC_e and $EC_{1:1}$ is 1.91 and the slope for the equation between EC_e and $EC_{1:5}$ is 3.12. These values indicate a non-linear trend in the mean values of EC based on the dilution of the lab procedure. This relationship is shown in Figure 3.1, d. Rather than decreasing linearly, as one would expect with a higher dilution, the mean is larger than expected with increasing dilutions. The standard deviation of the data also follows the same trend line for the three selected dilutions (Figure 3.1, e). Finally, the slopes of the regression equations for EC_e and $EC_{1:1}$, EC_e and $EC_{1:5}$, and $EC_{1:1}$ and $EC_{1:5}$ indicate a

non-linear relationship between the slope of the regression equation and dilution factor, which is shown in Figure 3.1, f. Using these relationships, we can make predictions about other dilution factors, such as 1:2 and 1:2.5 soil:water dilution extractions.

Characterization of dilution relationship for soluble cations (Na^+, Ca^{2+}, and Mg^{2+})

Soil test results for sodium (Na^+) are shown in Table 3.3. The least dilute extraction, approximately 1:0.5 for Na^+_e, produced the highest test values, whereas the most dilute, $Na^+_{1:5}$, produced the lowest test values, however, none of the dilutions produced significantly ($\alpha = 0.05$) different results. Differences in the soil test values between dilutions did result in dissimilarities in the regression equations comparing $Na^+_{1:1}$ and $Na^+_{1:5}$ dilutions with Na^+_e, and $Na^+_{1:1}$ with $Na^+_{1:5}$.

The linear regression equations for Na^+ are shown in Figure 3.2, a-c. All three relationships are statistically significant with p-values < 0.01. The slope for the regression equation between Na^+_e and $Na^+_{1:1}$ is 1.99 and the slope for the equation between Na^+_e and $Na^+_{1:5}$ is 6.16. These values indicate a non-linear trend in the mean values of Na^+ based on the dilution of the lab procedure. This relationship is shown in Figure 3.2, d. Rather than decreasing linearly, as one would expect with a higher dilution, the mean is larger than expected with increasing dilutions. The standard deviation of the data also follows the same trend line for the three selected dilutions (Figure 3.2, e). Finally, the slopes of the regression equations for Na^+_e and $Na^+_{1:1}$, Na^+_e and $Na^+_{1:5}$, and $Na^+_{1:1}$ and $Na^+_{1:5}$ indicate a non-linear relationship between the slope of the regression equation and dilution factor, which is shown in Figure 3.2, f. Using these relationships, we can make

predictions about other dilution factors, such as 1:2 and 1:2.5 soil:water dilution extractions.

Soil test results for calcium (Ca^{2+}) are shown in Table 3.4. The least dilute extraction, approximately 1:0.5 for Ca^{2+}_{e}, produced the highest test values, whereas the most dilute, $Ca^{2+}_{1:5}$, produced the lowest test values, however, none of the dilutions produced significantly ($\alpha = 0.05$) different results. Differences in the soil test values between dilutions did result in dissimilarities in the regression equations comparing $Ca^{2+}_{1:1}$ and $Ca^{2+}_{1:5}$ dilutions with Ca^{2+}_{e}, and $Ca^{2+}_{1:1}$ with $Ca^{2+}_{1:5}$.

The linear regression equations for Ca^{2+} are shown in Figure 3.3, a-c. All three relationships are statistically significant with p-values < 0.01. The slope for the regression equation between Ca^{2+}_{e} and $Ca^{2+}_{1:1}$ is 1.00 and the slope for the equation between Ca^{2+}_{e} and $Ca^{2+}_{1:5}$ is 1.61. These values indicate a linear trend in the mean values of Ca^{2+} for dilution factors from 0.5 to 1, but non-linear for dilution factors from 0.5 to 5. This relationship is shown in Figure 3.3, d. Rather than decreasing linearly, as one would expect with a higher dilution, the mean is larger than expected with increasing dilutions. The standard deviation of the data also follows the same trend line for the three selected dilutions (Figure 3.3, e). Finally, the slopes of the regression equations for Ca^{2+}_{e} and $Ca^{2+}_{1:1}$, Ca^{2+}_{e} and $Ca^{2+}_{1:5}$, and $Ca^{2+}_{1:1}$ and $Ca^{2+}_{1:5}$ indicate a non-linear relationship between the slope of the regression equation and dilution factor, which is shown in Figure 3.3, f. Using these relationships, we can make predictions about other dilution factors, such as 1:2 and 1:2.5 soil:water dilution extractions.

Soil test results for soluble magnesium (Mg^{2+}) are shown in Table 3.5 and the regression equations are shown in Figure 3.4. The results mimic those of sodium (Na^{+}) and are discussed above.

Characterization of dilution relationship for sodium adsorption ratio (SAR)

Soil test results for sodium adsorption ratio (SAR) are shown in Table 3.6. The least dilute extraction, approximately 1:0.5 for SAR_e, produced the highest test values, whereas the most dilute, $SAR_{1:5}$, produced the lowest test values, however, none of the dilutions produced significantly ($\alpha = 0.05$) different results. Differences in the soil test values between dilutions did result in dissimilarities in the regression equations comparing $SAR_{1:1}$ and $SAR_{1:5}$ dilutions with SAR_e, and $SAR_{1:1}$ with $SAR_{1:5}$.

Because the results for SAR are calculated using soluble cations, we expect the results to be similar to those of Na^{+}, Ca^{2+}, and Mg^{2+}. The linear regression equations for SAR are shown in Figure 3.5, a-c. All three relationships are statistically significant with p-values < 0.01. The slope for the regression equation between SAR_e and $SAR_{1:1}$ is 1.63 and the slope for the equation between SAR_e and $SAR_{1:5}$ is 2.63. These values indicate a non-linear trend in the mean values of SAR based on the dilution of the lab procedure. This relationship is shown in Figure 3.5, d. Rather than decreasing linearly, as one would expect with a higher dilution, the mean is larger than expected with increasing dilutions. The standard deviation of the data also follows the same trend line for the three selected dilutions (Figure 3.5, e). Finally, the slopes of the regression equations for SAR_e and $SAR_{1:1,}$ SAR_e and $SAR_{1:5}$, and $SAR_{1:1}$ and $SAR_{1:5}$ indicate a non-linear relationship between the slope of the regression equation and dilution factor, which is shown in

Figure 3.5, f. Using these relationships, we can make predictions about other dilution factors, such as 1:2 and 1:2.5 soil:water dilution extractions.

DISCUSSION

Traditionally, saturated paste extractions have been used to characterize saline and sodic soil properties in soils, and as such, management recommendations are based on these values (US Salinity Laboratory Staff, 1954). However, because many soil testing labs and private industries are using 1:1 and 1:5 soil to water dilutions to report test results to producers, it is important to understand differences in the results from the various laboratory methods (Franzen, 2007). The exact relationship of the differences vary based on parameter in question, however, the same trends exist across all salinity parameters.

Characterization of dilution relationship for electrical conductivity (EC)

The main objective for this research was to characterize how well one can predict EC_e using $EC_{1:1}$ and $EC_{1:5}$. The slope of the relationship between EC_e and $EC_{1:1}$ was 1.91±0.14, which differs from results in North Dakota that found the same relationship to be $y = 3.01x - 0.77$ where $x = EC_{1:1}$ and $y = EC_e$ on medium textured soils (Franzen, 2007). The relationship between EC_e and $EC_{1:5}$ was found to be $y = 3.12x + 1.75$ (R^2 = 0.64) in this study, where $y = EC_e$ and $x = EC_{1:5}$. These results were similar to a recent study completed in North Dakota, which showed, using the same methods, a relationship of $y = 2.74x + 3.01$ where $y = EC_e$ and $x = EC_{1:5}$ (He, et al., 2013). While results vary within the Northern Great Plains on soils affected by groundwater salinity, the

significance of the results show that a model can be developed to predict EC_e from $EC_{1:1}$ and $EC_{1:5}$. The relationship described in Figure 3.1,d shows the trend line for mean EC and the dilution factor. Rather than developing a relationship for each soil:water dilution and the saturated paste test values, this curve allows predictions to be made for any dilution. Breakthrough curves developed for various pore volumes of water and EC were similar to the results of this study (Shackelford, et al., 1999).

Some variation in the results may be explained by methodology within each lab procedure. In He, et al. (2013), researchers found that the methods used to process 1:5 extracts affected the resulting relationships between $EC_{1:5}$ and EC_e. Additionally, $EC_{1:1}$ and $EC_{1:5}$ have been shown to overestimate EC_e in calcareous soils, because the ion pair formation is interrupted in more dilute solutions (Amakor, et al., 2013), therefore, differences in salt and soil mineralogy may cause prediction models to vary.

Characterization of dilution relationship for soluble cations (Na^+, Ca^{2+}, and Mg^{2+})

The dilution relationships for Na^+, Ca^{2+}, and Mg^{2+} are not typically studied since the application falls mainly in calculating sodium adsorption ratio (SAR). However, one study found that predictions in Na^+ tended to be more reliable than predicting Ca^{2+} and Mg^{2+} concentrations from more dilute soil to water solutions (Al-Omran and Al-Mustafa, 1990). Using R^2 as an index for the reliability of prediction models, this study showed that Mg^{2+} (R^2 = 0.71 to 0.74) had the best fit regression models, followed by Na^+ (R^2 = 0.50 to 0.68) and Ca^{2+} had the most variability (R^2 = 0.48 to 0.75). As mentioned previously, the variability for Ca^{2+} is likely caused by the interruption of ion pairing in more dilute extracts (Amakor, et al., 2013), which may result in higher relative

concentrations of Ca^{2+} to be measured in the 1:1 and 1:5 extract solutions. This phenomenon can also explain the slope of 1 for the relationships of Ca^{2+}_{e} and $Ca^{2+}_{1:1}$ and the relatively low slope for Ca^{2+}_{e} and $Ca^{2+}_{1:5}$ and indicates the presence of Ca^{2+} salts with very low solubility ($CaCO_3$ and $CaSO_4$).

The Na^{+} minerals influencing salinity (NaCl, Na_2CO_3, Na_2SO_4) are highly soluble (161 to 264 g L^{-1}) (DeSutter, 2008), therefore, the relationship of Na^{+}_{e} with $Na^{+}_{1:1}$ and $Na^{+}_{1:5}$ should be dependent on the dilution factor. This was the case for the linear relationship of Na^{+}_{e} with $Na^{+}_{1:1}$ (slope = 1.99), but not for Na^{+}_{e} with $Na^{+}_{1:5}$ (slope = 6.16). The slope < 10 indicates that at higher dilutions, more sodium is in solution. This result could be related to the preferential affinity of divalent cations to the exchange sites on soil particles (DeSutter, 2008) in combination with the higher concentration of non-soluble salts in solution at higher dilutions (Amakor, et al., 2013). The higher concentrations of free Ca^{2+} will replace Na^{+} on the soil exchange sites, increasing soluble Na^{+}.

In this study, Mg^{2+} was the most suitable cation for predicting Mg^{2+}_{e} from $Mg^{2+}_{1:1}$ and $Mg^{2+}_{1:5}$. Magnesium salts can range in solubility from 2.5 g L^{-1} ($MgCO_3$) to 410 g L^{-1} ($MgCl_2$). In the Northern Great Plains region, the Mg^{2+} concentration can be highly variable, and little research has been done to evaluate the mineralogy of Mg^{2+} salts, so there is little explanation for these results. Similar to Na^{+}, the prediction of Mg^{2+}_{e} using $Mg^{2+}_{1:1}$ can be explained by the dilution of the extracts (slope = 1.97), but the slope for the regression equation of Mg^{2+}_{e} with $Mg^{2+}_{1:5}$ is again, less than 10, and cannot be explained by the dilution factor. In more dilute solutions, more soluble Mg^{2+} was measured, likely due to the interruption of ion pairing previously mentioned (Amakor, et

al., 2013). These results imply that less soluble Mg^{2+} salts ($MgCO_3$ or $MgSO_4$) dominate the mineralogy.

Characterization of dilution relationship for sodium adsorption ratio (SAR)

Because SAR is determined using the concentrations of soluble Na^+, Ca^{2+}, and Mg^{2+}, the accuracy of prediction models for SAR_e using $SAR_{1:1}$ and $SAR_{1:5}$ is directly related to the same prediction models for the soluble cations. While the linear regression equations for SAR were not identical to those of any of the cations, the results most closely mimicked the Na^+ and Mg^{2+} regression results. In Tables 3.3-3.5, soil test data shows that Na^+ and Mg^{2+} were the most abundant cations, relative to Ca^{2+}, so those regression results should be the most similar to the SAR results.

The results of regression analysis for predicting SAR_e using $SAR_{1:1}$ and $SAR_{1:5}$ were $y = 1.63x + 1.40$ ($R^2 = 0.47$) and $y = 2.63x + 0.81$ ($R^2 = 0.51$) respectively, and both relationships were significant with p-values < 0.00. Therefore, using soluble cation concentrations from dilute extractions is a viable method for accurately measuring SAR. Currently, many regional soil testing labs are predicting the sodium influence in soils using an ammonium acetate extraction (Chapman, 1965), which causes confusion when interpreting management recommendations. If soluble cations from 1:1 and 1:5 soil to water extractions can be used to predict SAR_e, testing lab results will agree with regional extension publications for managing sodic soils and producers will not need to have additional information in order to understand their salt-affected soils.

High levels of Mg^{2+} are another important consideration for calculating SAR in salt affected soils in South Dakota. Typically, Mg^{2+} and Ca^{2+} are considered to display

similar behavior in soil, and hence are not separated in the SAR calculation. However, studies have shown that Mg^{2+} is less effective than Ca^{2+} at preventing dispersion (Shainberg, et al., 1988), so in soils that have relatively high amounts of Mg^{2+} and Na^{+}, and relatively low amounts of Ca^{2+}, we would expect to see the effects of Na^{+} at SAR values much lower than 13.

CONCLUSIONS

This study aimed to establish relationships between saturated paste extractions, 1:1 soil to water extractions, and 1:5 soil to water extractions for various saline and sodic soil characteristics. In doing so, researchers hoped to create new methodology for soil testing labs in the Northern Great Plains to reduce confusion for producers interpreting saline and sodic soil test results. Results showed that all of the relationships analyzed were considered significant with p-values < 0.01, but the reliability of the prediction models varied based on the parameter of interest. Dilute extractions for Mg^{2+} were the best suited models, followed by EC, Na^{+}, SAR, and Ca^{2+} in decreasing order.

As Na^{+} becomes increasingly important in the Northern Great Plains region and in soils affected by groundwater salinity, it is crucial for producers to consider both EC and SAR (or other measures of Na^{+}) when making management decisions. With current practices, producers are advised to manage sodic soils using SAR values, but their soil test results are reported as a Na^{+} percentage of base saturation, causing confusion in interpretation. If soil testing labs could use the 1:1 and 1:5 soil to water extractions to determine soluble cation concentrations, they would not need to make a saturated paste extraction to accurately predict SAR, saving time and costs. Based on results from this

study, it is possible to create a prediction model for SAR_e using $SAR_{1:1}$ and $SAR_{1:5}$. Producers should consider managing for Na^+ below the currently recommended level of SAR > 13 due to high variability in the test results and the potential effect of the soluble Mg^{2+}.

Based on the results of this study, not only can linear regression relationships be developed between saturated paste extractions and various soil:water dilutions, but a non-linear relationship can also be established to predict the salinity parameters based on the dilution factor. Using this non-linear relationship for EC, Na^+, Ca^{2+}, Mg^{2+}, or SAR would allow any dilution results to be converted to any other dilution, including a saturated paste extraction. Soil texture should be taken into account when determining the dilution factor of the saturated paste extraction.

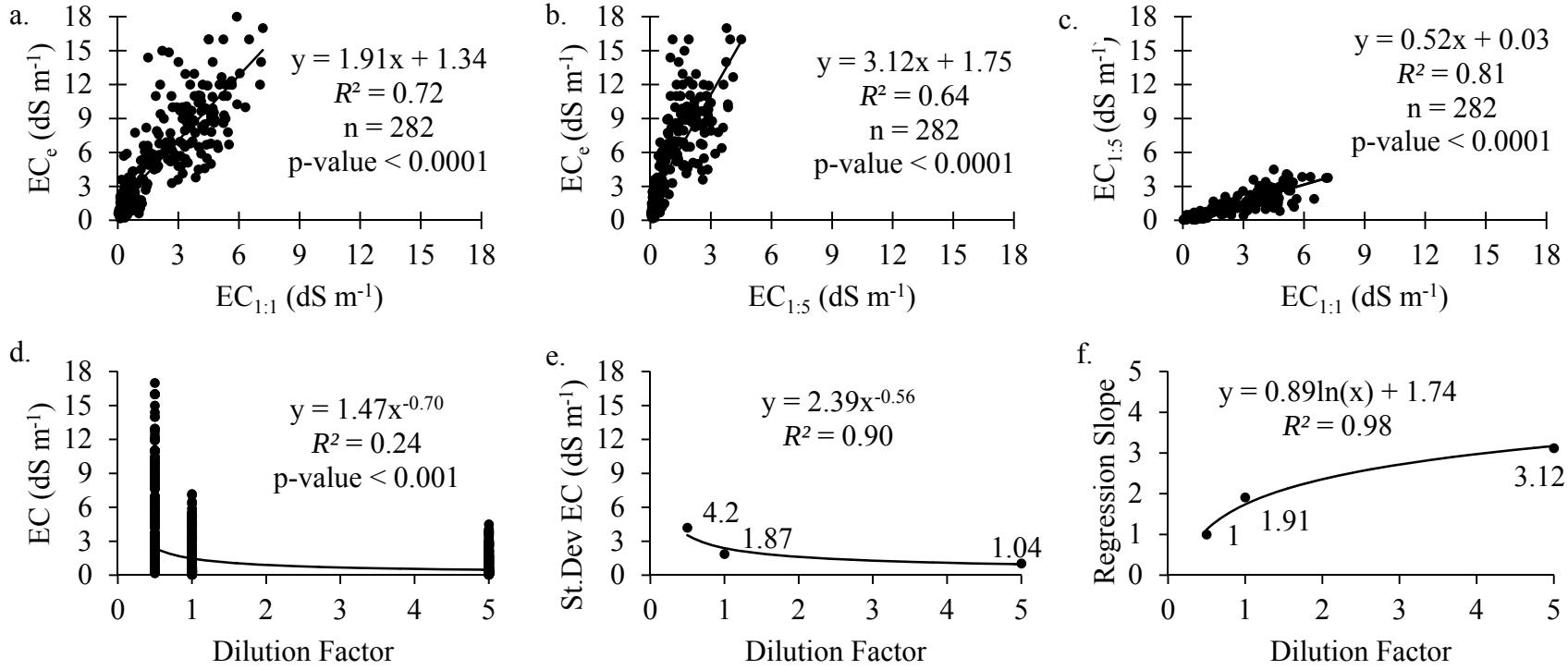

Figure 3.1. Selected dilution impacts on electrical conductivity (EC) values. a. EC measured using 1:1 soil:water ratio ($EC_{1:1}$) and saturated paste extraction (EC_e); b. EC measured using 1:5 soil:water ratio ($EC_{1:5}$) and saturated paste extraction (EC_e); c. EC measured using 1:1 soil:water ratio ($EC_{1:1}$) and 1:5 soil:water ratio ($EC_{1:5}$); d. EC values with dilutions (n = 282 for each dilution point) for each given dilution; e. EC standard deviation values with dilutions (n = 282 for each dilution point); f. Slope of the regression line with three soil:water dilutions (EC_e, $EC_{1:1}$, and $EC_{1:5}$) compared to EC_e (n = 282 for each dilution point). 44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Natrudolls, Argiudolls, Argialbolls [Soil Survey Division, 2014])

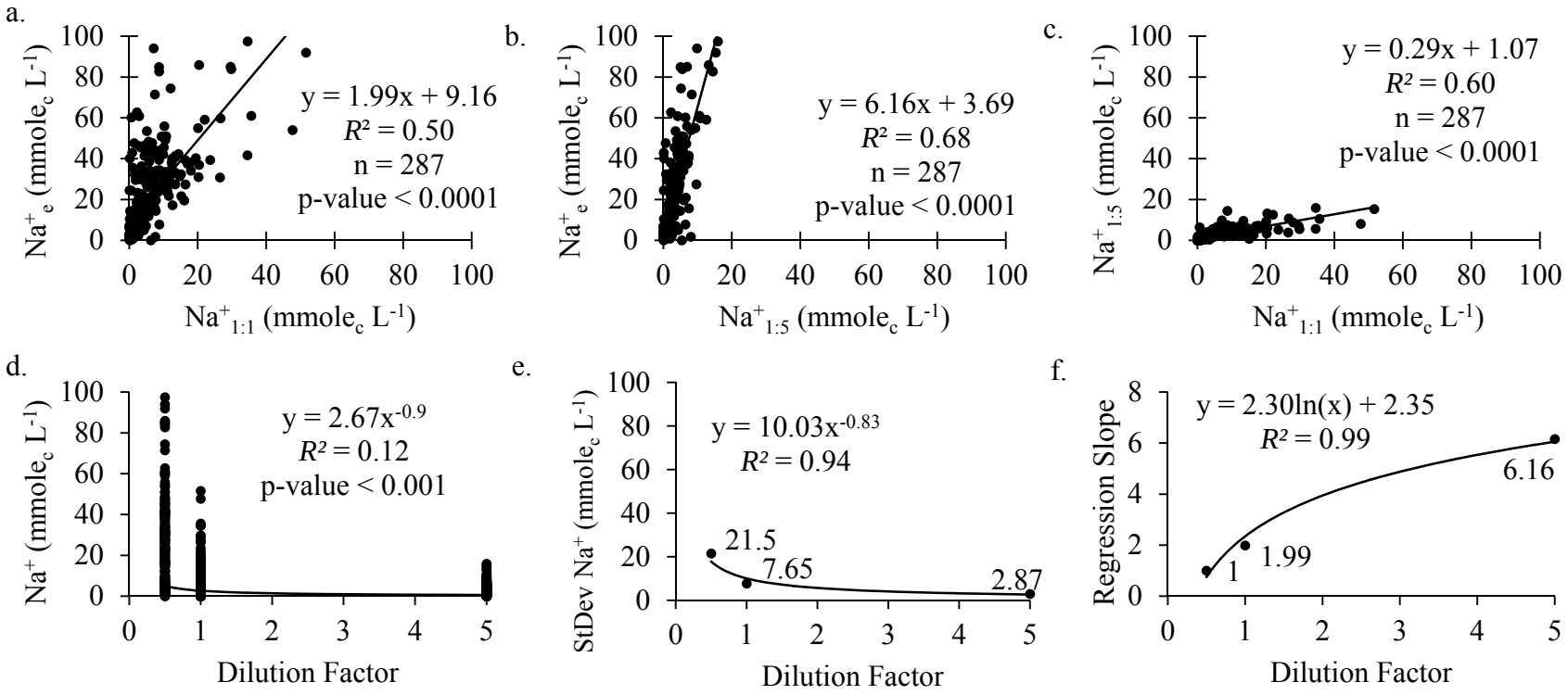

Figure 3.2. Selected dilution impacts on soluble sodium concentration (Na^+) values. a. Na^+ measured using 1:1 soil:water ratio ($Na^+_{1:1}$) and saturated paste extraction (Na^+_e); b. Na^+ measured using 1:5 soil:water ratio ($Na^+_{1:5}$) and saturated paste extraction (Na^+_e); c. Na^+ measured using 1:1 soil:water ratio ($Na^+_{1:1}$) and 1:5 soil:water ratio ($Na^+_{1:5}$); d. Na^+ values with dilutions (n = 287 for each dilution point); e. Na^+ standard deviation values (n = 287 for each dilution point); f. Slope of the regression line with three soil:water dilutions (Na^+_e, $Na^+_{1:1}$, and $Na^+_{1:5}$) compared to Na^+_e (n = 287 for each dilution point).
44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Natrudolls, Argiudolls, Argialbolls [Soil Survey Division, 2014])

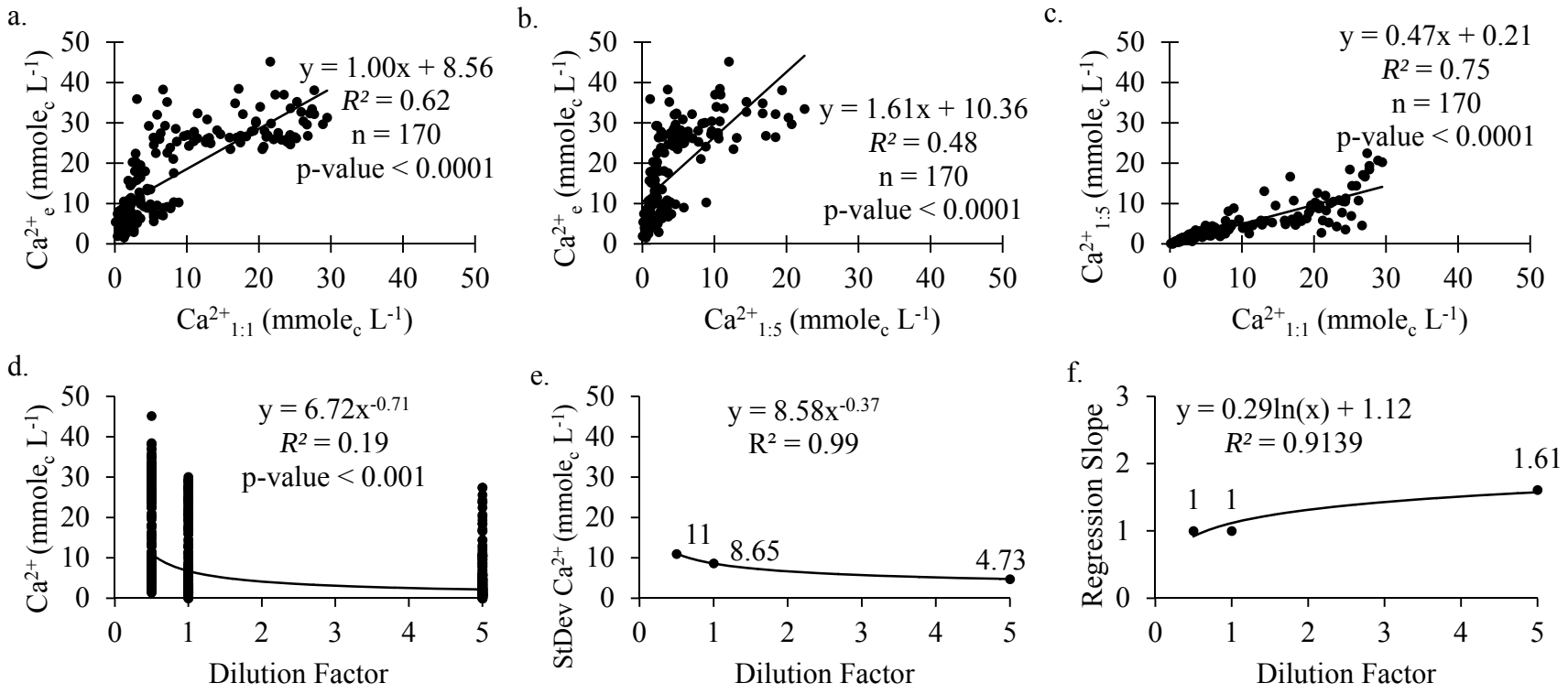

Figure 3.3. Selected dilution impacts on soluble calcium (Ca^{2+}) values. a. Ca^{2+} measured using 1:1 soil:water ratio ($Ca^{2+}_{1:1}$) and saturated paste extraction (Ca^{2+}_{e}); b. Ca^{2+}measured using 1:5 soil:water ratio ($Ca^{2+}_{1:5}$) and saturated paste extraction (Ca^{2+}_{e}); c. Ca^{2+} measured using 1:1 soil:water ratio ($Ca^{2+}_{1:1}$) and 1:5 soil:water ratio ($Ca^{2+}_{1:5}$); d. Ca^{2+} values with dilutions (n = 170 for each dilution point); e. Ca^{2+} standard deviation values with dilutions (n = 170 for each dilution point); f. Slope of the regression line with three soil:water dilutions (Ca^{2+}_{e}, $Ca^{2+}_{1:1}$, and $Ca^{2+}_{1:5}$) compared to Ca^{2+}_{e} (n = 170 for each dilution point).
44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Natrudolls, Argiudolls, Argialbolls [Soil Survey Division, 2014])

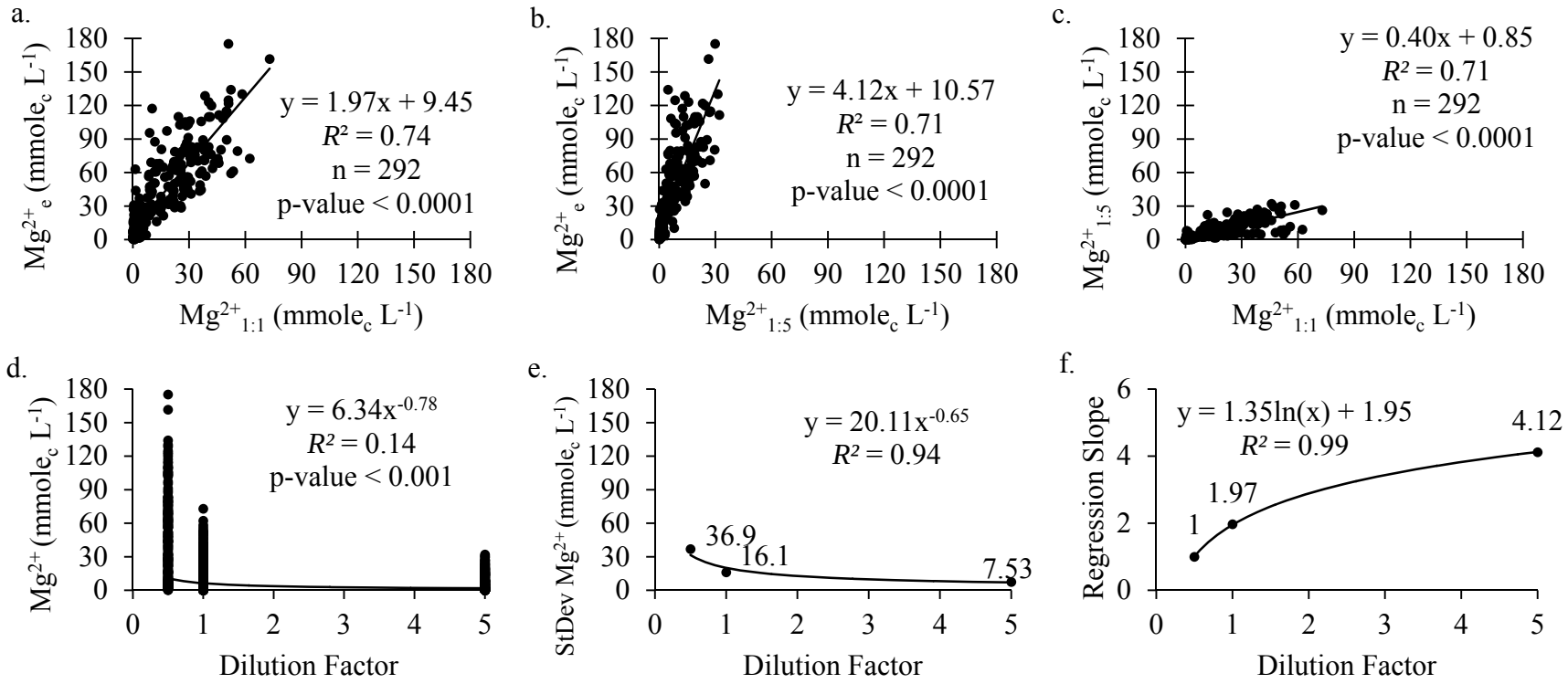

Figure 3.4. Selected dilution impacts on soluble magnesium (Mg^{2+}) levels. a. Mg^{2+} measured using 1:1 soil:water ratio ($Mg^{2+}_{1:1}$) and saturated paste extraction (Mg^{2+}_{e}); b. Mg^{2+}measured using 1:5 soil:water ratio ($Mg^{2+}_{1:5}$) and saturated paste extraction (Mg^{2+}_{e}); c. Mg^{2+} measured using 1:1 soil:water ratio ($Mg^{2+}_{1:1}$) and 1:5 soil:water ratio ($Mg^{2+}_{1:5}$); d. Mg^{2+} values with dilutions (n = 292 for each dilution point); e. Mg^{2+} standard deviation values with dilutions (n = 292 for each dilution point); f. Slope of the regression line with three soil:water dilutions (Mg^{2+}_{e}, $Mg^{2+}_{1:1}$, and $Mg^{2+}_{1:5}$) compared to Mg^{2+}_{e} (n = 292 for each dilution point).
44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Natrudolls, Argiudolls, Argialbolls [Soil Survey Division, 2014])

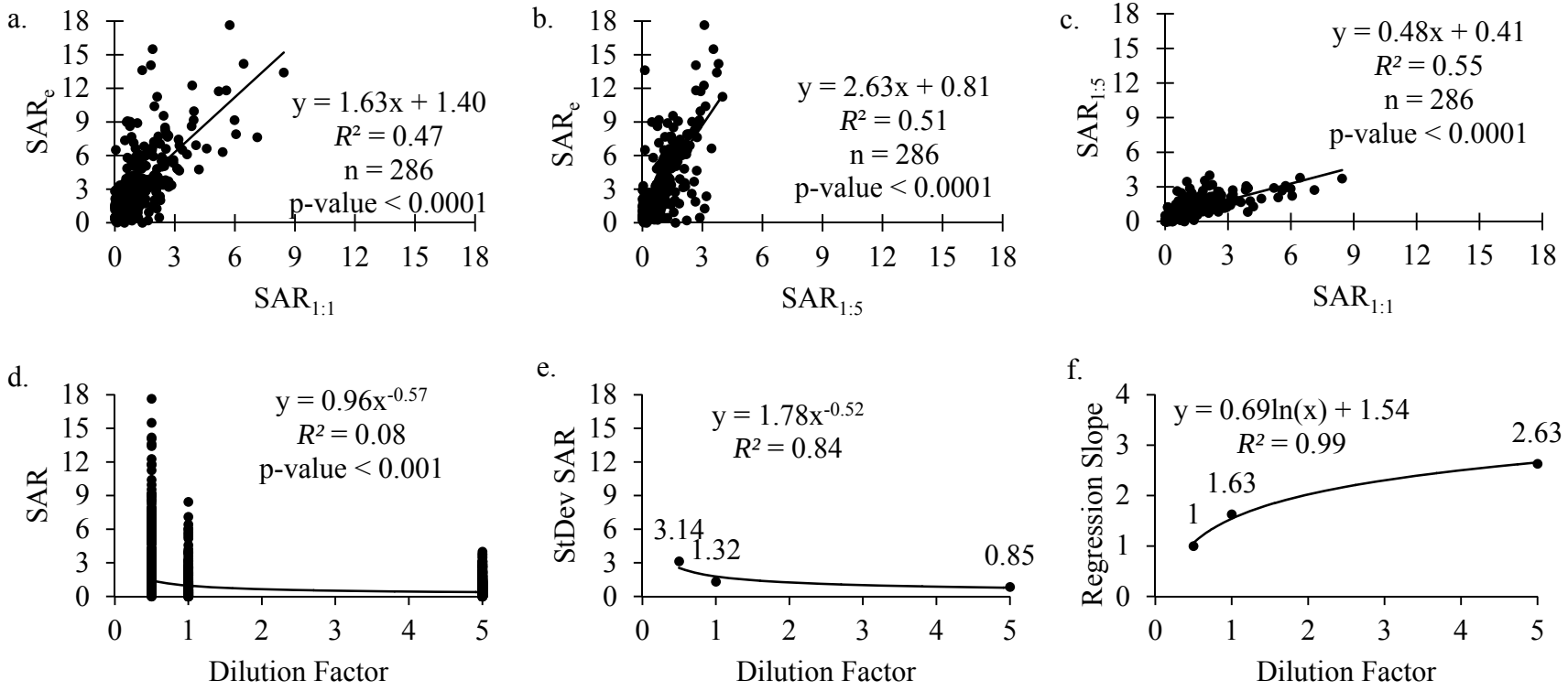

Figure 3.5. Selected dilution impacts on sodium adsorption ratio (SAR) values. a. SAR measured using 1:1 soil:water ratio ($SAR_{1:1}$) and saturated paste extraction (SAR_e); b. SAR measured using 1:5 soil:water ratio ($SAR_{1:5}$) and saturated paste extraction (SAR_e); c. SAR measured using 1:1 soil:water ratio ($SAR_{1:1}$) and 1:5 soil:water ratio ($SAR_{1:5}$); d. SAR values with dilutions (n = 286 for each dilution point); e. SAR standard deviation values with dilutions (n = 286 for each dilution point); f. Slope of the regression line with three soil:water dilutions (SAR_e, $SAR_{1:1}$, and $SAR_{1:5}$) compared to SAR_e (n = 286 for each dilution point).
44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Natrudolls, Argiudolls, Argialbolls [Soil Survey Division, 2014])

Table 3.1. Soil classification, slope, and parent material information for all soil samples used in this study. Samples were collected near Redfield*, South Dakota in June and July 2013 following corn (*Zea mays* L.) planting.

Map Unit Symbol	Series**	Slope (%)	Taxonomic Classification***	Parent Material
G720A	Great Bend-Beotia silt loams	0-2	Fine-silty, mixed, superactive, frigid Calcic Hapludolls Fine-silty, mixed, superactive, frigid Pachic Hapludolls	Fine-silty glaciolacustrine deposits
G722B	Great Bend-Zell silt loams	2-6	Fine-silty, mixed, superactive, frigid Calcic Hapludolls Coarse-silty, mixed, superactive frigid Typic Calciudolls	Fine-silty glaciolacustrine deposits
G866A	Harmony-Aberdeen silty clay loams	0-2	Fine, smectitic, frigid Pachic Argiudolls Fine, smectitic, frigid Glossic Natrudolls	Silty and clayey glaciolacustrine deposits
G868A	Winship-Tonka silt loams	0-1	Fine-silty, mixed, superactive, frigid Pachic Argiudolls Fine, smectitic, frigid Argiaquic Argialbolls	Fine silty-glaciolacustrine deposits

*44.9250° N, 97.4760° W
**(NRCS, 2014b)
***(Soil Survey Division, 2014)

Table 3.2. Soil test data for electrical conductivity (EC) for Spink County**, SD samples (n = 282).

	Mean (dS m^{-1})	**StDev**	**Max**	**Min**
EC_e*	5.18	4.20	18	0.18
$EC_{1:1}$	2.01	1.87	7.18	0.03
$EC_{1:5}$	1.01	1.04	4.5	0.05

*EC_e represents EC found from saturated paste extraction; $EC_{1:1}$ represents EC found from 1:1 soil:water ratio extraction; and $EC_{1:5}$ represents EC found from 1:5 soil:water ratio extraction

**44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Natrudolls, Argiudolls, Argialbolls [Soil Survey Division, 2014])

Table 3.3. Soil test data for soluble sodium concentration (Na^+) for Spink County**, SD samples (n = 287).

	Mean ($mmole_c\ L^{-1}$)	**StDev**	**Max**	**Min**
Na^+_e*	19.7	21.5	101	0
$Na^+_{1:1}$	5.25	7.65	51.6	0
$Na^+_{1:5}$	2.59	2.87	15.9	0

*Na^+_e represents Na^+ found from saturated paste extraction; $Na^+_{1:1}$ represents Na^+ found from 1:1 soil:water ratio extraction; and $Na^+_{1:5}$ represents Na^+ found from 1:5 soil:water ratio extraction

**44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Natrudolls, Argiudolls, Argialbolls [Soil Survey Division, 2014])

Table 3.4. Soil test data for soluble calcium concentration (Ca^{2+}) for Spink County**, SD samples (n = 170).

	Mean ($mmole_c\ L^{-1}$)	**StDev**	**Max**	**Min**
Ca^{2+}_e*	17.6	11.0	45.2	1.56
$Ca^{2+}_{1:1}$	9.02	8.65	29.5	0.12
$Ca^{2+}_{1:5}$	4.47	4.73	22.5	0.02

*Ca^{2+}_e represents Ca^{2+} found from saturated paste extraction; $Ca^{2+}_{1:1}$ represents Ca^{2+} found from 1:1 soil:water ratio extraction; and $Ca^{2+}_{1:5}$ represents Ca^{2+} found from 1:5 soil:water ratio extraction

**44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Natrudolls, Argiudolls, Argialbolls [Soil Survey Division, 2014])

Table 3.5. Soil test data for soluble magnesium concentration (Mg^{2+}) for Spink County**, SD sample (n = 292).

	Mean ($mmole_c\ L^{-1}$)	**StDev**	**Max**	**Min**
Mg^{2+}_e*	36.8	36.9	175	0.24
$Mg^{2+}_{1:1}$	13.9	16.1	72.9	0.00
$Mg^{2+}_{1:5}$	6.11	7.53	32.1	0.04

*Mg^{2+}_e represents Mg^{2+} found from saturated paste extraction; $Mg^{2+}_{1:1}$ represents Mg^{2+} found from 1:1 soil:water ratio extraction; and $Mg^{2+}_{1:5}$ represents Mg^{2+} found from 1:5 soil:water ratio extraction

**44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Natrudolls, Argiudolls, Argialbolls [Soil Survey Division, 2014])

Table 3.6. Soil test data for sodium adsorption ratio (SAR) for Spink County**, SD samples (n = 286).

	Mean	**StDev**	**Max**	**Min**
SAR_e*	3.47	3.14	17.6	0
$SAR_{1:1}$	1.26	1.32	8.44	0
$SAR_{1:5}$	1.01	0.85	4.00	0

*SAR_e represents SAR found with soluble cations from saturated paste extraction; $SAR_{1:1}$ represents SAR found with soluble cations from 1:1 soil:water ratio extraction; and $SAR_{1:5}$ represents SAR found with soluble cations from 1:5 soil:water ratio extraction
**44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Natrudolls, Argiudolls, Argialbolls [Soil Survey Division, 2014])

REFERENCES

Al-Omran, A.M. and W.A. Al-Mustafa. 1990. Reliability of 1:1, 1:2 and 1:5 Weight Extracts for Expressing Salinity in Light-Textured Soils of Saudi Arabia. Agricultural Sciences 2: 321-329.

Amakor, X.N., A.R. Jacobson and G.E. Cardon. 2013. Improving Estimates of Soil Salinity from Saturation Paste Extracts in Calcareous Soils. Soil Science Society of America Journal 77: 792.

Chapman, H.D. 1965. Cation-Exchange Capacity. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. ACSESS. p. 891-901.

DeSutter, T.M. 2008. Problems in production fields: Saline and sodic soils. In: S. L. e. al., editor Soil science: step-by-step field analysis. . Soil Science Society of America Special Publication, Madison, WI. p. 183-200.

Franzen, D. 2007. Managing Saline Soils in North Dakota. NDSU Extension Service. file:///C:/Users/Owner/Downloads/Saline%20and%20Sodic%20Soils%20%20(1).pdf (accessed 28 Dec. 2014).

He, Y., T. DeSutter, D. Hopkins, X. Jia and D.A. Wysocki. 2013. Predicting ECe of the saturated paste extract from value of EC1:5. Canadian Journal of Soil Science 93: 585-594.

Hogg, T.J. and J.L. Henry. 1984. Comparison of 1:1 and 1:2 suspensions and extracts with saturation extract in estimating salinity in Saskatchewan soils. Canadian Journal of Soil Science 64: 699-704.

Khorsandi, F. and F.A. Yazdi. 2011. Estimation of Saturated Paste Extracts' Electrical Conductivity from 1:5 Soil/Water Suspension and Gypsum. Communications in Soil Science and Plant Analysis 42: 315-321.

National Soil Survey Center. 1996. Soil Survey Methods Laboratory Manual USDA-NRCS.

NRCS. 2014a. Major Land Resource Area Explorer. USDA-NRCS, http://apps.cei.psu.edu/mlra/ (accessed 01 Dec. 2014).

NRCS. 2014b. Web Soil Survey. USDA-NRCS, http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx (accessed 01 Dec. 2014).

Rhoades, J.D. 1982. Soluble Salts. Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties. ASA-SSSA, Madison, WI.

SAS Institute. 2011. SAS® 9.3 SQL Procedure User's Guide.

Shackelford, C.D., M.A. Malusis, M.J. Majeski and R.T. Stern. 1999. Electrical Conductivity Breakthrough Curves. Journal of Geotechnical and Geoenvironmental Engineering 125: 260-270.

Shainberg, I., N. Alperovitch and R. Keren. 1988. Effect of Magnesium on the Hydraulic Conductivity of Na-Smectite-Sand Mixtures. Clay and Clay Minerals 36: 432-438.

Slavich, P. and G. Petterson. 1993. Estimating the electrical conductivity of saturated paste extracts from 1:5 soil, water suspensions and texture. Soil Research 31: 73-81.

Soil Survey Division. 2014. Official Soil Series Descriptions. USDA-NRCS, https://soilseries.sc.egov.usda.gov/osdname.asp (accessed 01 Dec. 2014)

Sonmez, S., D. Buyuktas, F. Okturen and S. Citak. 2008. Assessment of different soil to water ratios (1:1, 1:2.5, 1:5) in soil salinity studies. Geoderma 144: 361-369.

US Salinity Laboratory Staff. 1954. Diagnosis and Improvement of Saline and Alkali Soils. In: L. Richards, editor Agricultural Handbook 60. USDA, Riverside, CA.

Zhang, H., J.L. Schroder, J.J. Pittman, J.J. Wang and M.E. Payton. 2005. Soil Salinity Using Saturated Paste and 1:1 Soil to Water Extracts. Soil Science Society of America Journal 69: 1146.

CHAPTER 4

FIELD SCALE SPATIAL VARIABILITY OF SALINE AND SODIC SOIL PROPERTIES IN THE SOUTHERN BLACK GLACIATED PLAINS OF SOUTH DAKOTA, USA (MLRA 55C)

ABSTRACT

Row crop production in Eastern South Dakota (SD), USA is primarily dominated by corn (*Zea mays* L.), soybeans (*Glycine max* L.), and wheat (*Triticum* spp.). In the past two decades, the area of salt affected soils has increased, causing producers to change management practices in order to maintain productivity on these soils. The objectives of this study were to: 1) identify the locations of salt affected soils, and 2) how the salts are spatially related on a field scale. Basic soil cores were collected from various points across fields in Day and Spink Counties, SD (MLRA 55C) and analyzed for electrical conductivity (EC), soluble cation concentrations (Na^+, Ca^{2+}, and Mg^{2+}), and sodium adsorption ratio (SAR). The spatial distribution of these soil properties was then estimated using the ordinary kriging approach. Results from this study show that all data were spatially autocorrelated (Global Moran's I values > 0), but interpolation using ordinary kriging produced low R^2 values and high estimation errors because of the higher spatial variability. While the interpolation results were not conclusive, they showed that the salt affected soil area increased with depth. Soils that lack saline and sodic soil problems at the surface, but have moderate saline and sodic soil problems in the subsurface should be considered high risk for developing more severe limitations in the future when capillary and groundwater rise could bring soil solutes to the soil surface.

INTRODUCTION

Salt affected soils are a major limitation to crop production in the Northern Great Plains and worldwide (Franzen, 2007). Producers must be able to understand the saline and sodic soil problems in their fields in order to make proper management decisions, such as crop selection, amendment application (for sodic soils), and water management. Crop selections are based on salt-tolerance recommendations and perennial vegetation can be used to reclaim salt affected soils (Franzen, 2007). Chemical amendments, such as gypsum, may be needed to leach excess sodium (DeSutter, 2008). In the Northern Great Plains, salt affected soils are often the result of salty groundwater near the soil surface (Franzen, 2007), so subsurface drainage may also be considered to manage salt affected soils (US Salinity Laboratory Staff, 1954). Research and extension publications typically make recommendations for salt-affected soil management using electrical conductivity (EC) and sodium adsorption ratio (SAR).

In addition to understanding how the various saline and sodic soil properties are related to one another and to crop production, it is important to understand the spatial distribution of saline and sodic soil properties. The origin of soil salts in the Northern Great Plains differs from that of most saline and sodic soils studied, so research is needed to characterize these soils. One of the primary differences is the source of the salts. In the Northern Great Plains, salinity occurs due to the subsurface transport of salts with capillary water to the surface soil, whereas in the arid and semi-arid regions of the west salts are primarily provided with irrigation water. The soils of the Black Glaciated Plains (MLRA 55C [NRCS, 2014a]) were formed in glacial till that overlays Cretaceous marine

shale from a prehistoric ocean, so groundwater brings salts from the shale bedrock to the glaciated surface soils (Daniels, 1987). These critical differences suggest that salt identification criteria developed for surface irrigated agricultural systems will have limited applications for the Northern Great Plains.

Previous studies have examined the spatial distribution of soil salinity (Corwin, et al., 2003; Douaik, et al., 2005; Ganjegunte and Braun, 2011; Guo, et al., 2013; Li, et al., 2013; Li, et al., 2015; Rhoades, et al., 1990; Taghizadeh-Mehrjardi, et al., 2014), but in order to understand why this study is needed, we must consider why the spatial distribution of salts in groundwater derived salt affected soils is different from past studies. According to Provin and Pitt (2012), salt buildup can occur in five different conditions including irrigating with water high in salts, in soils with poor drainage allowing for evaporation, in soils naturally high in salts, in areas where the water table is shallow, and in seepage zones. Soils in the Northern Great Plains are unique in that they are medium to fine textures, causing poor drainage at times, the soils themselves are naturally high in salts from the parent materials, and the water table is shallow. The mechanics of water and salt movement are then also unique in these soils compared to traditionally studied saline and sodic soils. Thus, the objectives of this study were to establish a baseline field scale spatial distribution of EC, Na^{+}, Ca^{2+}, Mg^{2+}, and SAR at two sites in Eastern South Dakota, where row crop production has been increasingly affected by saline and sodic soils, and to identify high risk areas where saline and sodic soil problems may occur in the future.

MATERIALS AND METHODS

Sample collection and processing

Soil samples were collected from the Northern Great Plains, USA in Day (Pierpont) and Spink (Redfield) Counties, South Dakota (lat. 44.9250° – 45.4751° N, long. 97.8359° – 98.4760° W, MLRA 55C). The sampling depths were 0-7.5, 7.5-15, 15-30, and 30-60 cm. The soils used for this study were all formed in glacially deposited parent materials. Full detail on the USDA taxonomic classifications can be found in Table 4.1 and 4.2. Figure 4.1 shows the soil map for Pierpont and Figure 4.2 shows the soil map for Redfield. Samples were collected in November 2013 using two separate sampling schemes. First, samples were taken on a 62 m by 62 m grid (1 acre). At Pierpont, additional samples were collected at varying distances from two center points – 1, 2.5, 5, 10, 20, 40, and 80 m – and in eight different directions – N, NE, E, SE, S, SW, W, and NW from the center point. These samples will further be described as rose samples, due to the likeness of the sampling scheme to a compass rose. All samples were geo-referenced using a Magellan Professional handheld global positioning system (GPS) unit. Samples were air dried to 40^{o}C, ground, passed through a 2 mm sieve, and stored in plastic bags.

Laboratory analysis for electrical conductivity (EC), soluble cations (Na^{+}, Ca^{2+}, and Mg^{2+}), and sodium adsorption ratio (SAR)

Soil EC and soluble cation concentrations were determined from a saturated extract using methods described by Rhoades (1982). To obtain the saturated extract, approximately 150 g of soil was mixed with ultra-pure water until sample was completely

saturated. Saturated samples were left to equilibrate for at least 8 hours. Soil solution was extracted through vacuum filtration using a Büchner funnel apparatus. Extract samples were stored at 4°C until analyzed. EC was determined using a conductivity probe (South Dakota – PC 2700, Oakton Instruments, Vernon Hills, IL) (Rhoades, 1982). Cation concentrations of Na^+, Ca^{2+}, and Mg^{2+} were measured using flame atomic adsorption spectrophotometry (200 A, Buck Scientific, Norwalk, CT) (Rhoades, 1982). Na^+ and Mg^{2+} samples were diluted using ultra-pure water and Ca^{2+} samples were diluted using a calcium suppressant solution (La_2O_3·HCl solution) (National Soil Survey Center, 1996). Resulting concentrations were converted from ppm to $mmole_c\ L^{-1}$. Sodium adsorption ratio (SAR) was calculated using Equation 5.1.

$$SAR = \frac{[Na^+]}{\left(\frac{[Ca^{2+}] + [Mg^{2+}]}{2}\right)^{1/2}} \quad (5.1)$$

Spatial analysis

Geo-referenced soil data for EC, Na^+, Ca^{2+}, Mg^{2+}, and SAR was analyzed for spatial distribution characteristics using ArcMap 10.0 software. Both the original soil test data and log-transformed test data were evaluated for their spatial distribution. Spatial autocorrelation, or degree of spatial clustering, was described using Global Moran's I values, where values > 0 indicated positive spatial autocorrelation (clustering of soil test values) and values < 0 indicated negative spatial autocorrelation (random scattering of soil test values). If soil test data was positively spatially autocorrelated, distribution maps were created using spherical ordinary kriging. Previous studies on interpolating soil test

data have shown that both inverse distance weighting (IDW) and ordinary kriging are viable options (Corwin, et al., 2003), but kriging was chosen for this study so that the range (a), nugget (C_0), and partial sill (C) of the distribution could be determined. Kriging equations were calibrated using 75% of the total sample set (Pierpont: n = 152; Redfield: n = 31) and the remaining 25% were used to validate the model (Pierpont: n = 51; Redfield: n = 10). Semi-variograms were used to determine the kriging model using Equation 5.2, where γ(h) is the semi-variance for lag distance h, N is the number of samples, A is the test value for sample i, X is the location of sample i. and $X_i + h$ represents the distance between two sample locations (Nielsen and Wendroth, 2003). The directional distribution of the soil testing data was also determined and used as a

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [A_i(X_i) - A_i(X_i + h)]^2 \quad (5.2)$$

RESULTS

Soil test results for electrical conductivity (EC), soluble cations (Na^+, Ca^{2+}, and Mg^{2+}), and sodium adsorption ratio (SAR)

Soil test data for Pierpont non-transformed samples, Redfield non-transformed samples, Pierpont log-transformed samples, and Redfield non-transformed samples are shown in Tables 4.3-4.6, respectively. The non-transformed data for both Pierpont and Redfield were not normally distributed, as tested by the Shapiro-Wilk Normality test, and positive skewness values indicated that the data was skewed to the right. Due to the

clustered and hot spot nature of saline and sodic soil properties, skewed distributions were expected. The coefficient of variation (CV) values were improved when the data was log-transformed, but the many of the data were still not normally distributed. While the skewness values are close to zero in the log-transformed data, the kurtosis values, which show the peakedness of the data, are very low. Kurtosis values less than 3 indicate a flat, broad distribution. No one parameter had consistently lower CV values, nor were there any trends in the data distribution with depth or location.

Spatial autocorrelation and directional distribution

Non-transformed and log-transformed data results for spatial autocorrelation are shown in Tables 4.7 and 4.8, respectively. All data exhibited positive spatial autocorrelation (Moran's I values greater than 0). Moran's I values approaching +1, indicate data that are more clustered and are more easily mapped using geo-statistical methods such as kriging. EC and Mg^{2+} were consistently more positively autocorrelated when compared to Na^{+}, Ca^{2+}, and SAR. Non-transformed and log-transformed Pierpont samples were more positively autocorrelated than the respective Redfield samples. These results indicate that EC and Mg^{2+} kriging maps will likely be more accurate than Na^{+}, Ca^{2+}, and SAR maps, and Pierpont maps may be more accurate than Redfield maps.

Soil parameters for this study were considered anisotropic, meaning the distribution of the soil test values were directionally dependent, rather than randomly distributed throughout the field (isotropic distribution). For example, if soil samples were collected along transects at different angles across the field, the error in predicting intermittent values for each transect may be the same at every angle, or may vary. When

the error of the prediction is independent of the angle sampled, data is isotropic, but if error varies based on the angle, data is anisotropic. The angle of the transect with the least error was considered the angle of the ellipse for the studied data. The degree of the angle of ellipse is determined in a counterclockwise direction from the east-west origin, therefore, values from 0 to 90° indicate samples that are oriented northeast-southwest, with values close to 0° being more oriented with the east-west origin and values close to 90° being more oriented with the north-south origin. Angle values between 90 and 180° are oriented northwest-southeast. Pierpont angles mostly fell between 0 and 90°, showing that the soil test data tended to be oriented northeast-southwest. Redfield angles were often close to 90°, which showed that the soil test data tended to be oriented north-south. Some possible reasons for this distribution are discussed in the next section.

Spatial distribution using ordinary kriging

Tables 4.9 and 4.10 show the statistical results from ordinary kriging. The root mean square error (RMSE) and coefficient of determination (R^2) were found using the measured and predicted values of the validation set, which contained 25% of the samples (Pierpont: n = 51; Redfield: n = 10) and were not included in calculating the original kriging model. Data for EC and SAR at both locations had consistently lower RMSE values, however, the SAR R^2 values were quite lower than the EC R^2 values. The RMSE and R^2 values for the soluble cations, Na^+, Ca^{2+}, and Mg^{2+}, varied with depth, but the RMSE values were typically higher for the soluble cations when compared to the EC and SAR data, and the R^2 values were typically lower for the soluble cations when compared to the EC and SAR data. At both Pierpont and Redfield, the log-transformation improved

the RMSE and R^2 values for all soil test parameters. The range (a), nugget semi-variance (C_0), and partial-sill semi-variance (C) were used to prepare the kriged maps.

Interpolation maps generated using ordinary kriging are shown in Figures 4.3-4.22, with Pierpont non-transformed data for EC, Na^+, Ca^{2+}, Mg^{2+}, and SAR in Figures 4.3-4.7, respectively, Pierpont log-transformed data in Figures 4.8-4.12, Redfield non-transformed data in Figures 4.13-4.17, and Redfield log-transformed data in Figures 4.18-4.22. For the Pierpont maps, the saline and sodic soil properties were more concentrated in the southwest corner of the field and the north central section of the field. The soil map in Figure 5.1 shows that the Nahon-Aberdeen-Exline complex in the southwest corner of the field, which are all classified as Natrudolls, so it is expected that the EC, soluble cations, and SAR values would be elevated in that area. However, the north central section of the field is classified as a Kranzburg-Brookings soil complex, which are both taxonomically Hapludolls, so the high values of EC, soluble cations and SAR cannot be explained by the soil map. At Redfield, saline and sodic soil properties were higher on the east half of the field, where Aberdeen soils were common (shown in Figure 4.2).

For both Pierpont and Redfield, the most severe areas of the field are shown on both the non-transformed and log-transformed maps, however, some small differences exist between the two transformations. The maps for the log-transformed data are smoother than the respective non-transformed data, a trend which is especially evident for the EC maps for Pierpont (Figures 4.3 and 4.8). The salt-affected area of each field is shown larger using the non-transformed data when compared to the log-transformed data. This difference can be seen in Figures 4.6 and 4.11 for the Pierpont Mg^{2+} distributions. The parameter distribution with depth was similar for all parameters at both locations. At

the surface, the hot spots tended to be more severe, but with depth, the salt-affected areas were more widespread than at the surface.

DISCUSSION

Soil test results for electrical conductivity (EC), soluble cations (Na^+, Ca^{2+}, and Mg^{2+}), and sodium adsorption ratio (SAR)

Mapping saline and sodic soil properties can be difficult due to the nature of their distribution, both spatially and statistically. In this study, EC, Na^+, Ca^{2+}, Mg^{2+}, and SAR were highly variable with high CV values and positive skewness values. While log-transformation of the data helped to lower CV values, most of the parameters were still not normally distributed. Other studies have seen similar distribution trends for soil properties and found that log-transformed data was well suited for creating prediction maps (Akramkhanov, et al., 2014; Aldabaa, et al., 2015; Li, et al., 2015; Yang, et al., 2009). No soil test parameter had consistently lower CV values, nor were there any statistical trends in the data distribution with depth or location.

Spatial autocorrelation and directional distribution

Saline and sodic soil properties tend to be found in clusters in the Northern Great Plains, so the results for spatial autocorrelation were expected. All the parameters tested were positively spatially autocorrelated. EC and Mg^{2+} consistently had higher Moran's I values, and for all soil test parameters, Moran's I values tended to decrease with depth. Similar results have been seen for the spatial autocorrelation of micronutrients with depth (Liu, et al., 2013). Because Mg^{2+} was the most abundant cation, it was likely the

dominant factor influencing EC, so the correlation between EC and Mg^{2+} was expected. Pierpont soil test parameters were more positively spatially correlated than the respective parameters for the Redfield site. This is likely due to the distance between samples at Pierpont compared to Redfield. At Pierpont, additional rose samples were collected in order to improve the accuracy of the prediction models. Those samples were not collected at Redfield, so the shortest distance between Redfield samples was 62 m, compared to 1 m at Pierpont. Work done by Nielsen and Wendroth (2003) showed that for soil water content, as lag distance increased (m), the autocorrelation coefficient decreased, which agrees with the findings of this study.

Soil properties at both Pierpont and Redfield were anisotropically distributed. At Pierpont, the general distribution direction was oriented from northeast to southwest across the field and at Redfield, results for the angle of ellipse showed the parameter distribution direction oriented from north to south. In order to understand these results, it is important to consider how salts move across a landscape. Soil salts in the Northern Great Plain are groundwater derived, and as such, move with the groundwater (Daniels, 1987), so soil salts should be distributed where the groundwater is nearest to the surface, or in areas of low elevation (Franzen, 2007). Elevation maps would show that the areas of the lowest elevation at Pierpont are located in the southwest corner of the field and in the south central section of the field at Redfield. Not only are salts most prevalent in low-lying areas due to groundwater, but lateral water flow from higher elevations will also transport soluble salts to lower elevations, a concept most studied for soil nutrient and pollutant transport (King, et al., 2014, Mbonimpa, et al., 2014).

Spatial distribution using ordinary kriging

Because apparent EC using electromagnetic induction is a quick way to assess field scale salinity and is typically strongly correlated with EC_e, many studies have been done to create prediction models for soil EC. However, there are a variety of methods that can be used to create the prediction maps, so results from different studies are difficult to compare. Akramkhanov, et al. (2014), Douaik, et al. (2005), and Li, et al. (2013) estimated the spatial distribution of EC using kriging models similar to this study, and found that the R^2 values between predicted and measured EC to be approximately 0.70-0.90. For this study, the R^2 values for EC ranged from 0.74-0.80 for Pierpont data and 0.31-0.61 for Redfield data. The Redfield samples are likely not as well correlated due to the smaller number of samples and larger distance between sampling points.

While the spatial distribution of EC has been extensively studied, the same is not true for Na^+, Ca^{2+}, Mg^{2+}, and SAR. The results for these parameters are highly variable between Pierpont and Redfield and vary greatly with depth, so it may not be appropriate to place too much importance on the range, nugget, and partial sill values found for these data. However, the overall trends seen in the prediction maps should be considered. One important trend was the depth distribution of saline and sodic soil properties. While the most severe problems were seen in the surface soils, the overall salt affected area increased with depth for all parameters at both sites. The subsurface salt affected areas represent soils at high risk for developing saline and sodic soil problems in the future, since the solutes can readily be moved to the surface through capillary water flow or as the groundwater rises (Franzen, 2007). This depth distribution is extremely important for growers to consider when managing saline and sodic soils.

CONCLUSIONS

It is important to understand the spatial distribution of saline and sodic soil properties in order for farmers in Eastern South Dakota to better manage salt-affected areas in their fields, due to the adverse effects of soil salts on crop yield and soil health. The origin of soil salts in the Northern Great Plains differs from that of most saline and sodic soils studied, so research is needed to characterize these soils. The objective of this study was to determine the field scale spatial distribution of EC, Na^{+}, Ca^{2+}, Mg^{2+}, and SAR at two sites in Eastern South Dakota, where row crop production has been increasingly affected by saline and sodic soils.

Statistically, the soil test data in this study was highly variable for all parameters, which was likely caused by the tendency of saline and sodic soil properties to be distributed in hot spots. Using a log-transformation lowered the CV values for the data, but very few of the parameters were normally distributed, even after the transformation. Spatial distribution models are best fit for normally distributed data, so the heterogeneity of the data set limited the prediction accuracy. All data was positively spatially autocorrelated, so ordinary kriging was chosen as the method for creating prediction maps.

Statistical results for the semi-variograms were inconsistent for the soil test parameters, but some important overall trends were seen in the prediction maps. For many of the soil maps, using both non-transformed and log-transformed data and at both locations, saline and sodic soil properties were most severe in the top 7.5 cm of the soil, but with depth, the salt-affected area increased in size. The salts present from 30-60 cm may not be affecting crop production currently, but may be transported closer to the

surface through capillary water flow and rising groundwater. Therefore, soils with subsurface salinity and sodicity should be identified and considered high risk. Future work should be done to develop better models to predict subsurface salt distribution. In addition to the spatial distribution of saline and sodic soil properties, it would also be beneficial to study how the distribution changes temporally.

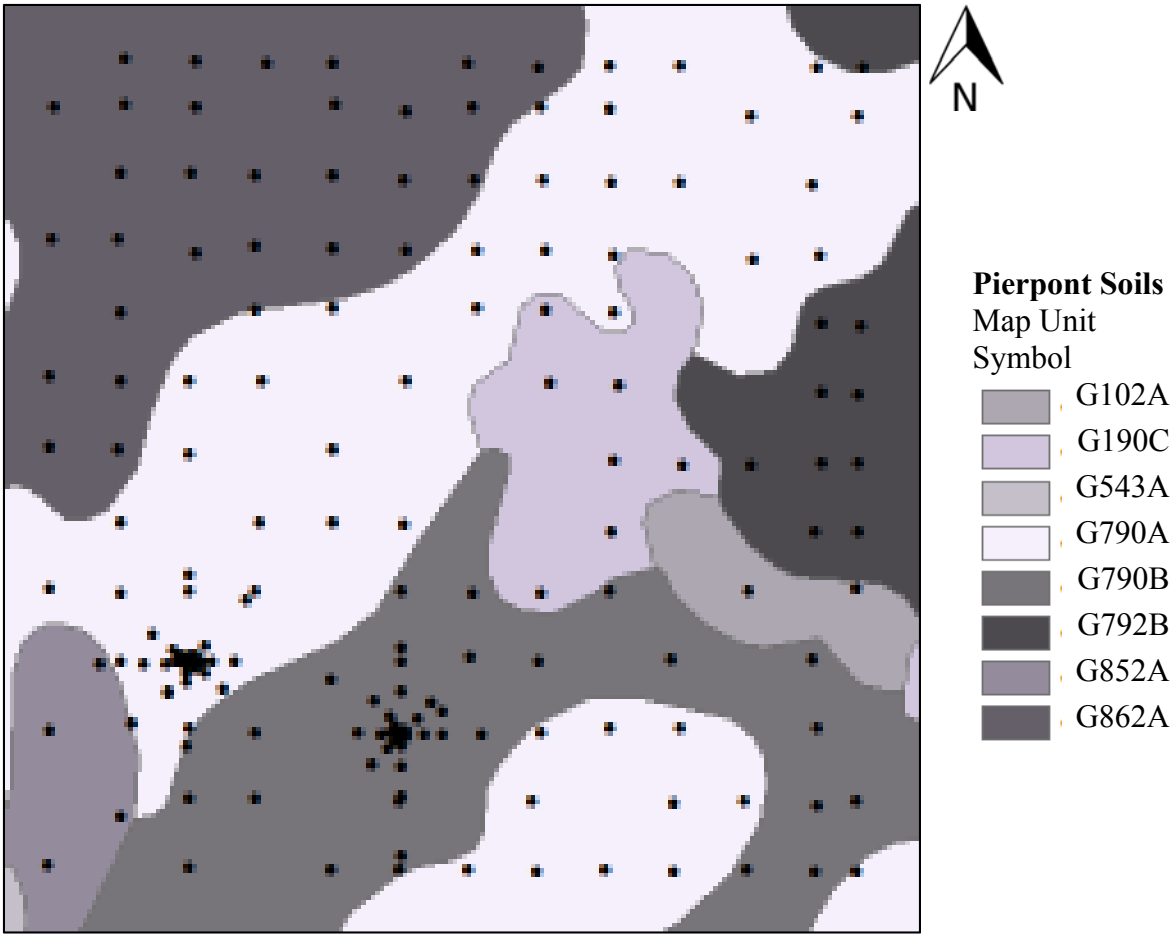

Figure 1. Soil map of 65 hectare (160 acre) field at Pierpont*, SD. Descriptions of each soil map unit are listed in Table 4.1.
*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls [Soil Survey Division, 2014])

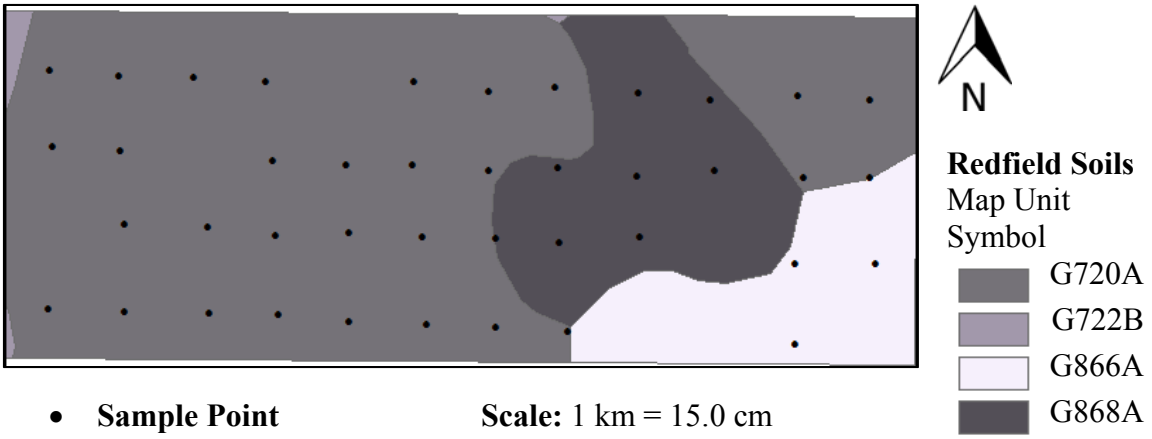

Figure 4.2. Soil map of 18 hectare (45 acre) field at Redfield*, SD. Descriptions of each soil map unit are listed in Table 2.
*44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls [Soil Survey Division, 2014])

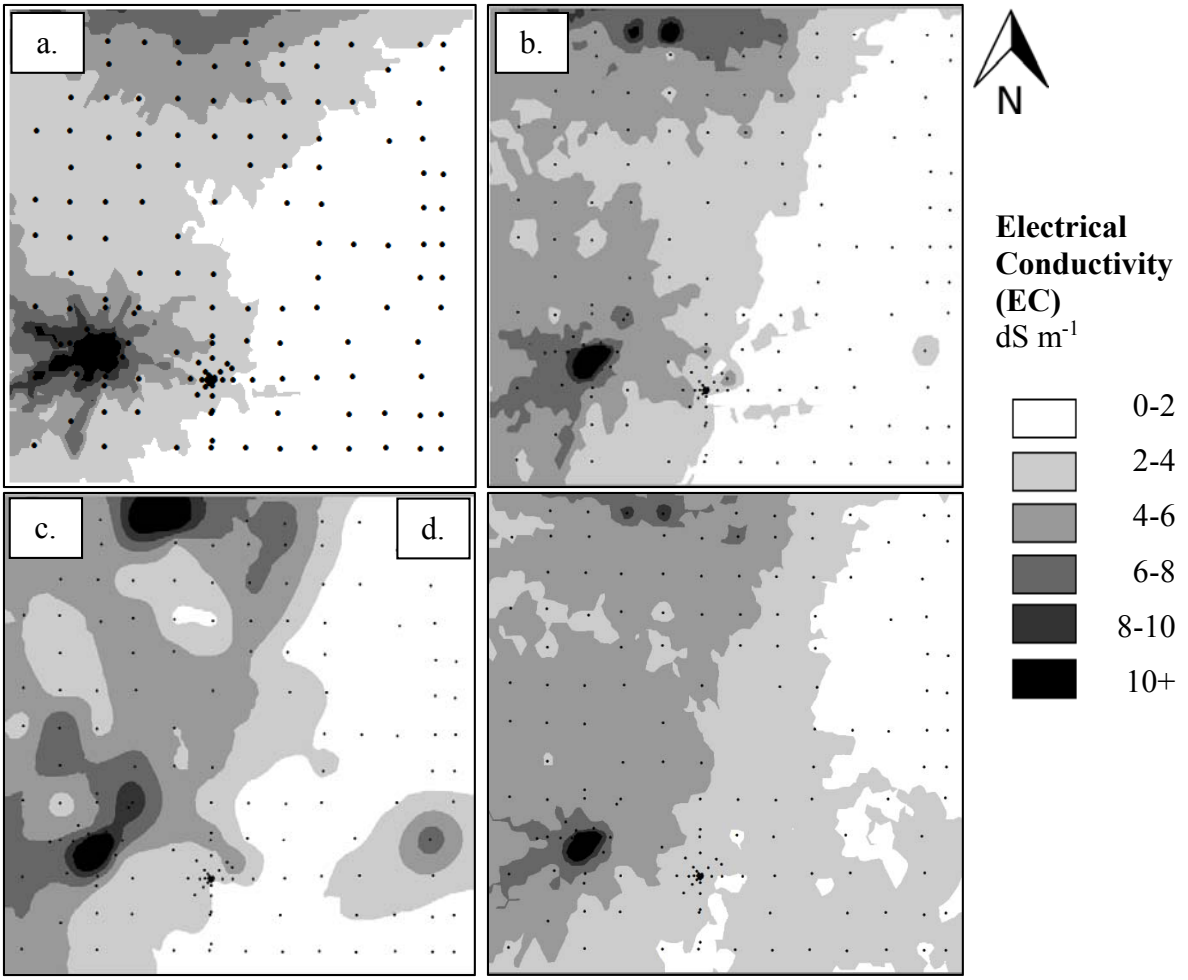

Figure 4.3. Electrical conductivity (EC) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Pierpont*, SD samples. Untransformed data was interpolated using ordinary kriging.
*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls [Soil Survey Division, 2014])

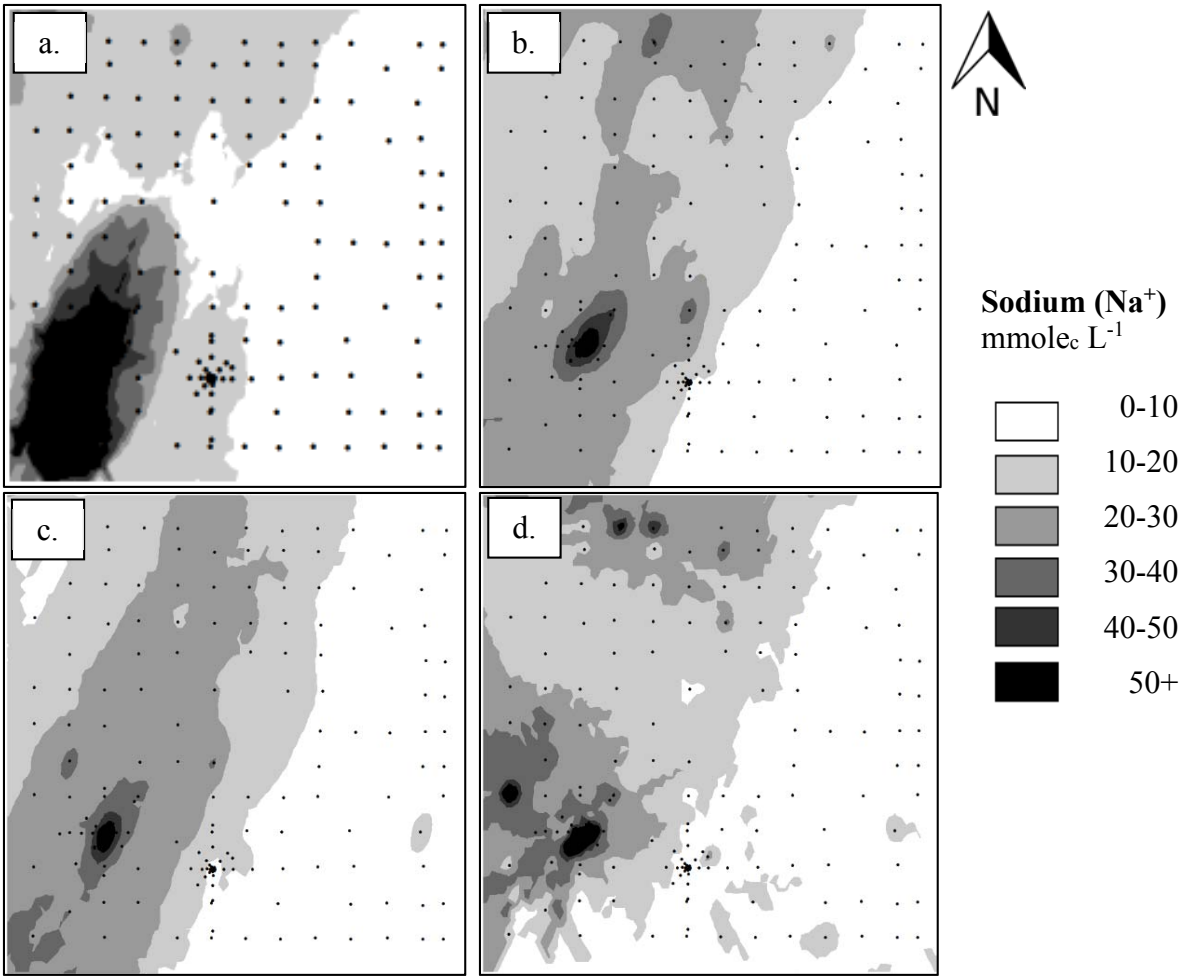

Figure 4.4. Sodium (Na^+) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Pierpont*, SD samples. Untransformed data was interpolated using ordinary kriging.
*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls [Soil Survey Division, 2014])

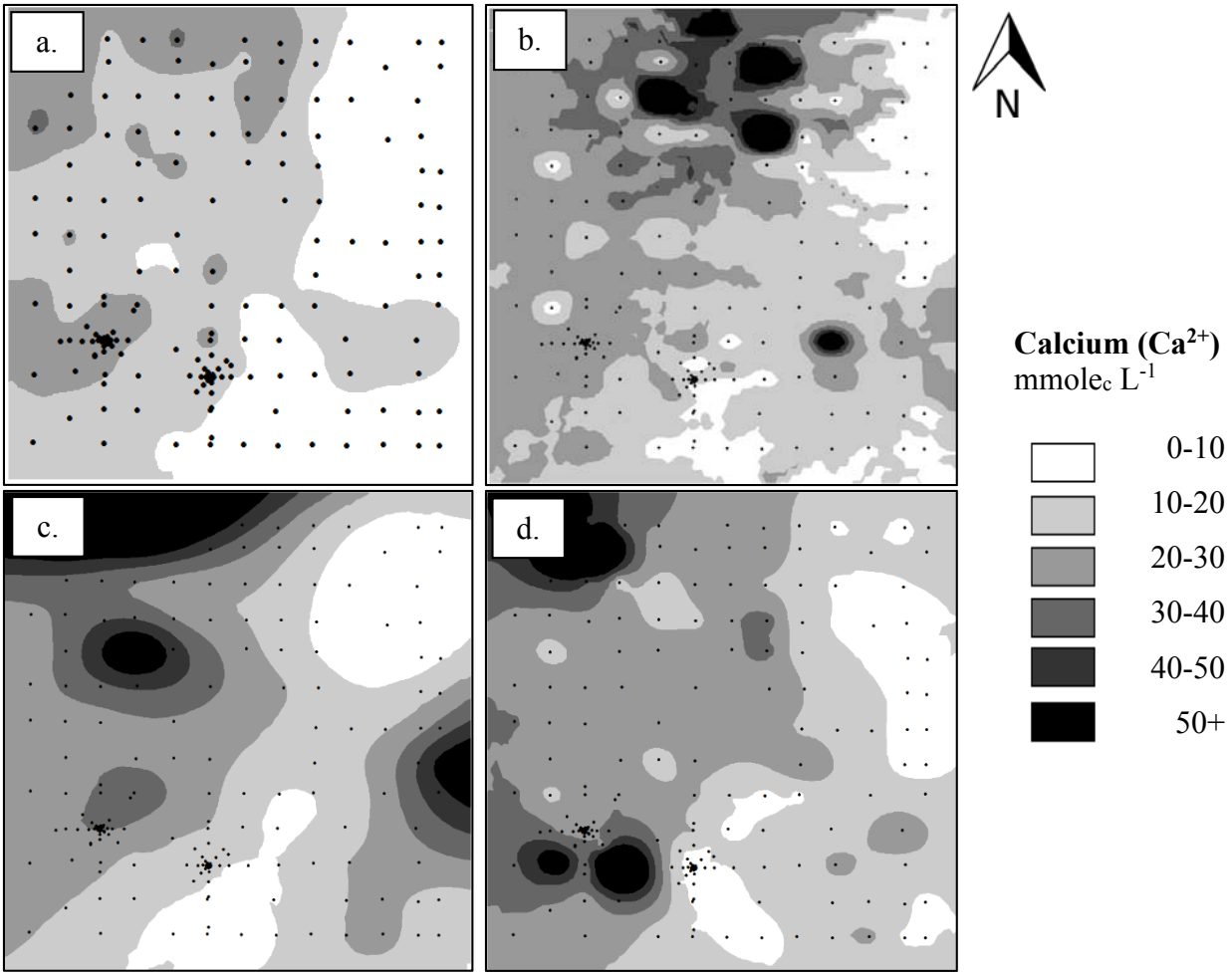

Figure 4.5. Calcium (Ca^{2+}) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Pierpont*, SD samples. Untransformed data was interpolated using ordinary kriging.
*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls [Soil Survey Division, 2014])

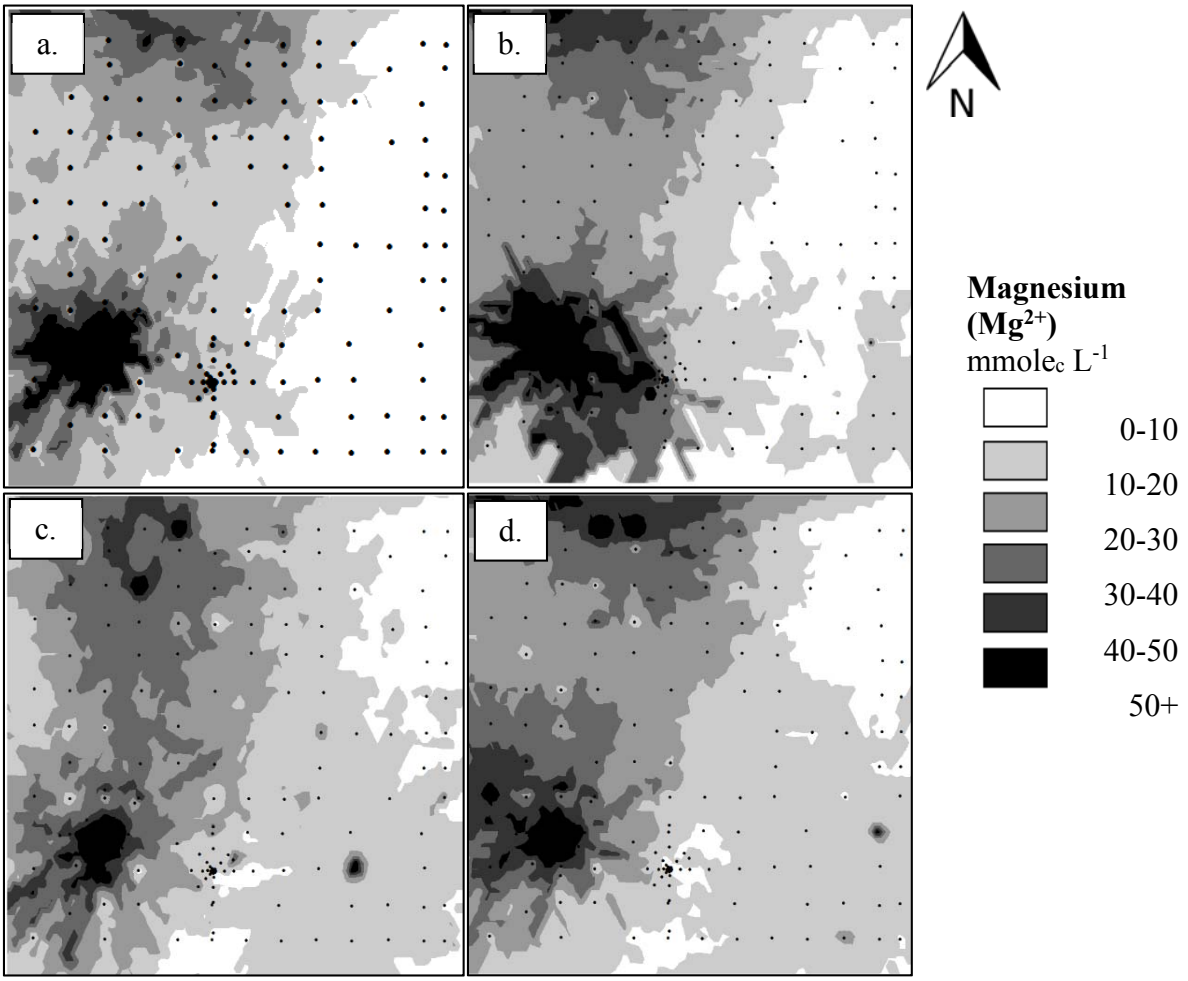

Figure 4.6. Magnesium (Mg^{2+}) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Pierpont*, SD samples. Untransformed data was interpolated using ordinary kriging.
*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls [Soil Survey Division, 2014])

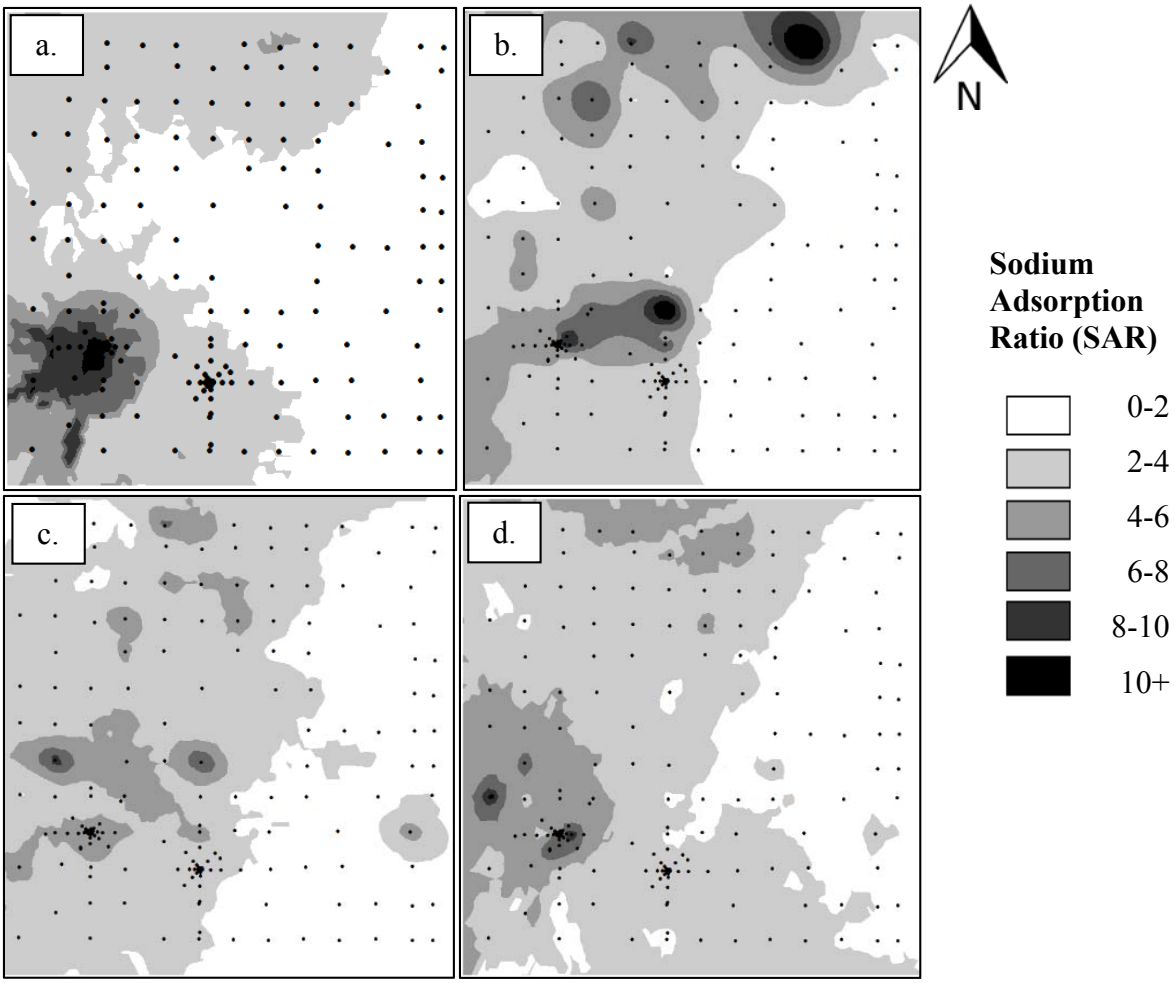

Figure 4.7. Sodium adsorption ratio (SAR) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Pierpont*, SD samples. Untransformed data was interpolated using ordinary kriging.
*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls [Soil Survey Division, 2014])

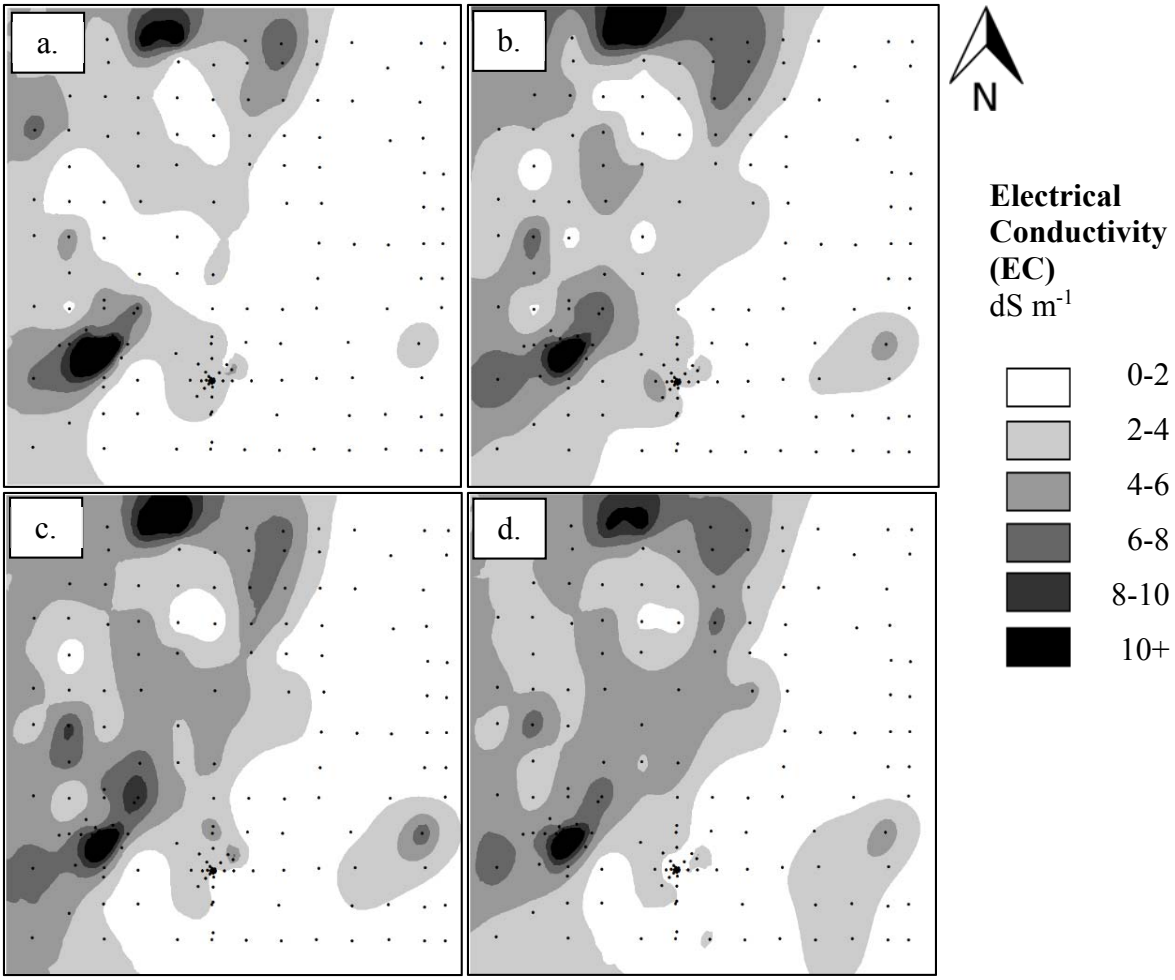

Figure 4.8. Electrical conductivity (EC) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Pierpont*, SD samples. Log-transformed data was interpolated using ordinary kriging.
*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls [Soil Survey Division, 2014])

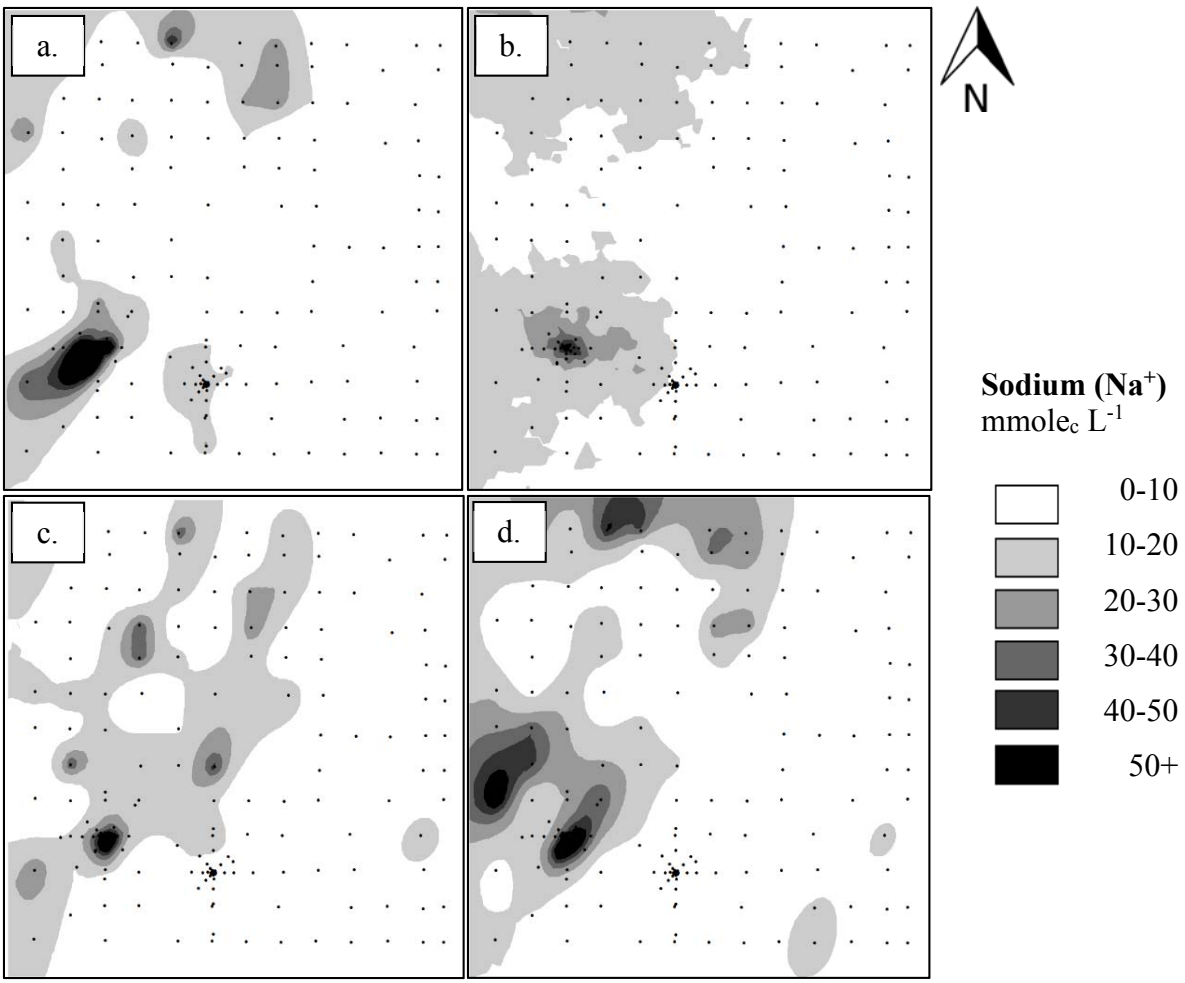

Figure 4.9. Sodium (Na^+) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Pierpont*, SD samples. Log-transformed data was interpolated using ordinary kriging.
*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls [Soil Survey Division, 2014])

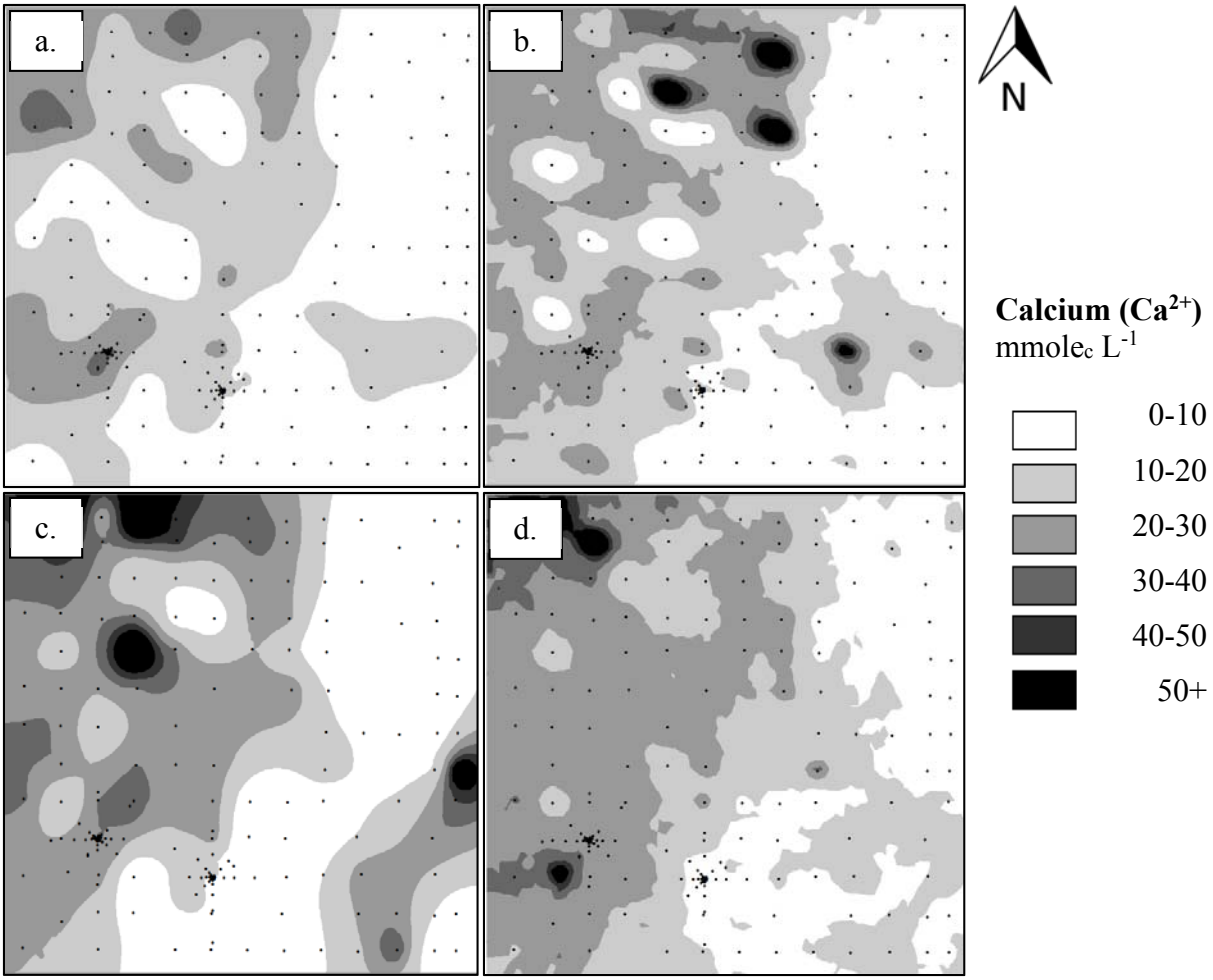

Figure 4.10. Calcium (Ca^{2+}) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Pierpont*, SD samples. Log-transformed data was interpolated using ordinary kriging.
*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls [Soil Survey Division, 2014])

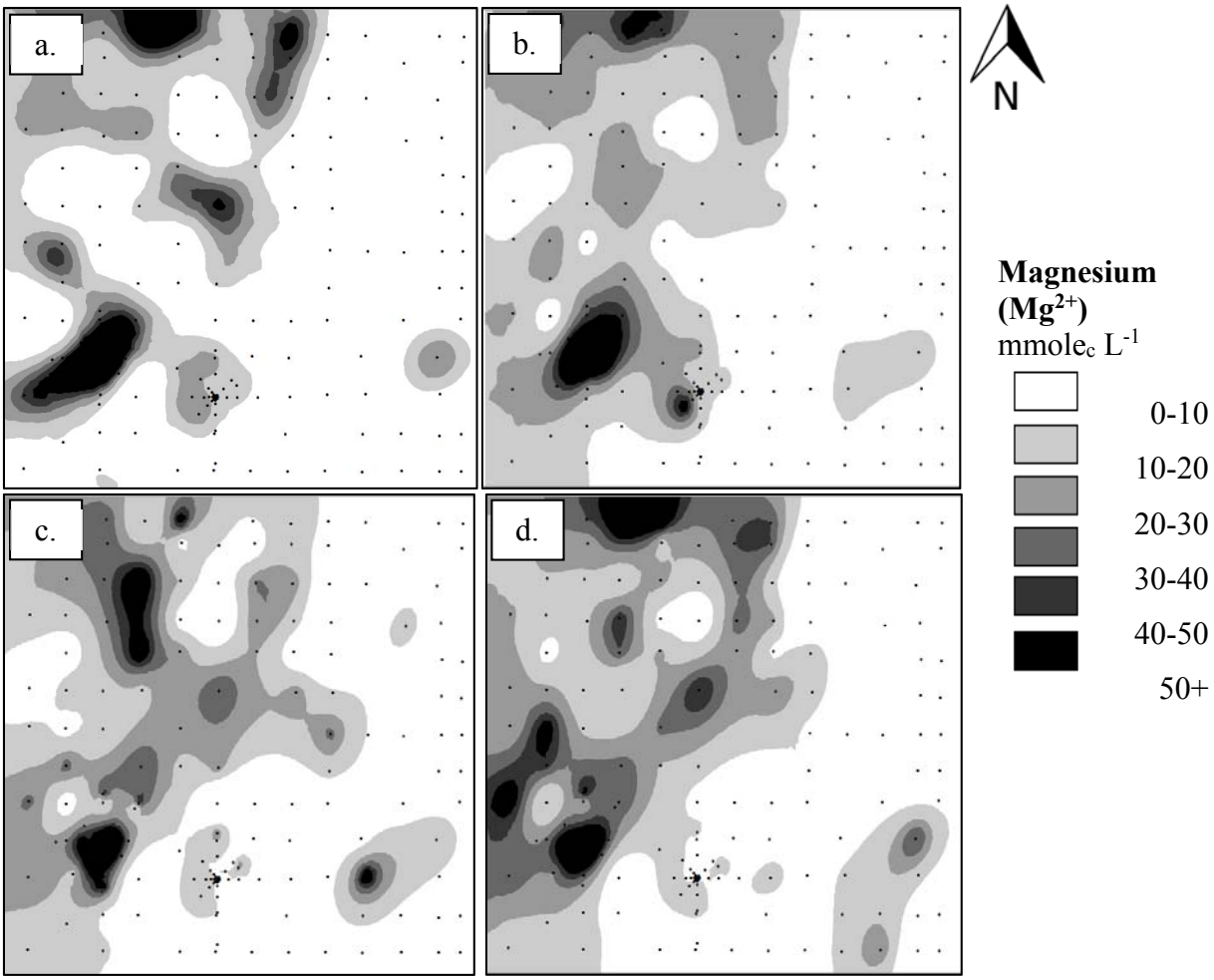

Figure 4.11. Magnesium (Mg^{2+}) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Pierpont*, SD samples. Log-transformed data was interpolated using ordinary kriging.
*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls [Soil Survey Division, 2014])

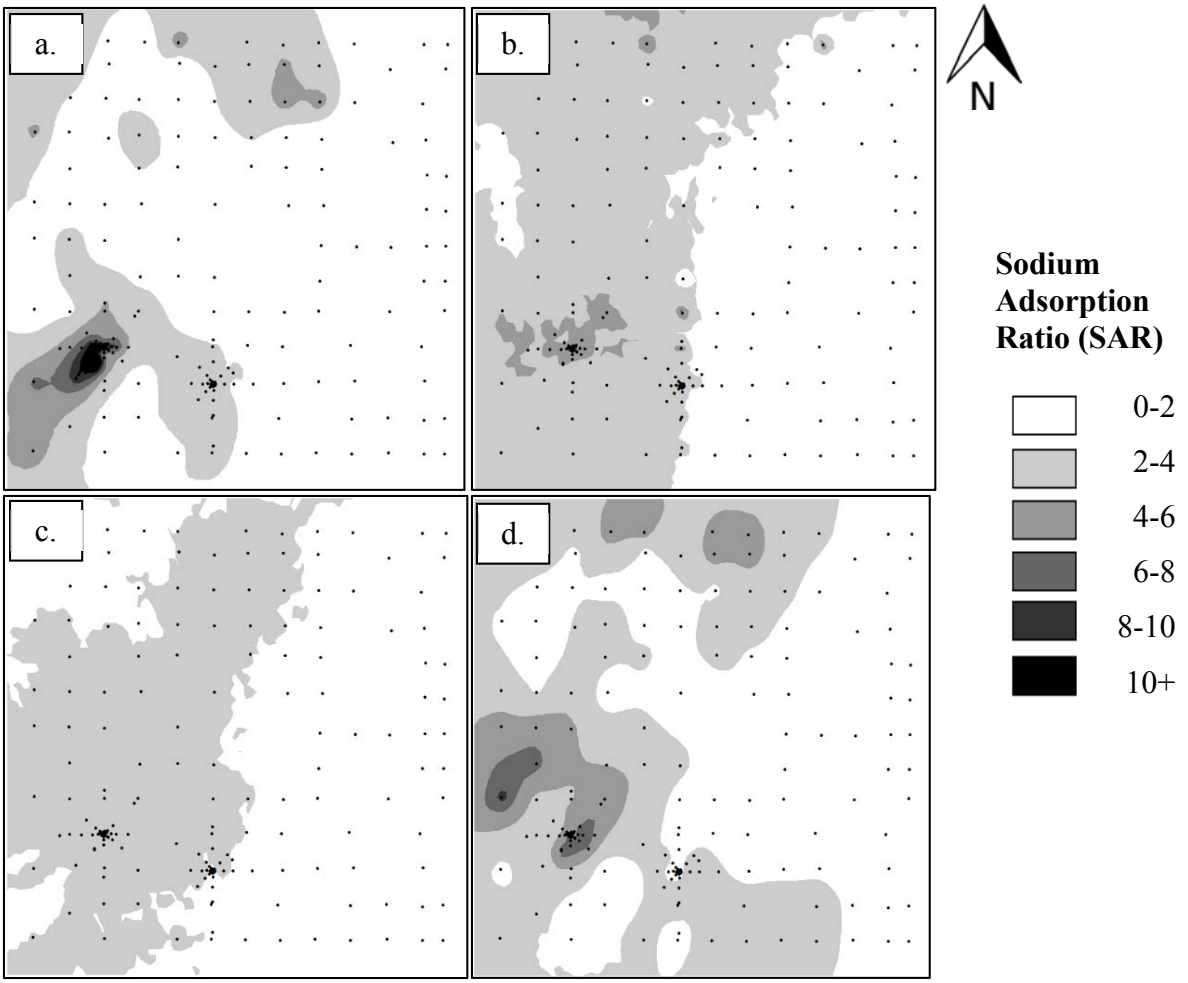

Figure 4.12. Sodium adsorption ratio (SAR) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Pierpont*, SD samples. Log-transformed data was interpolated using ordinary kriging.
*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls [Soil Survey Division, 2014])

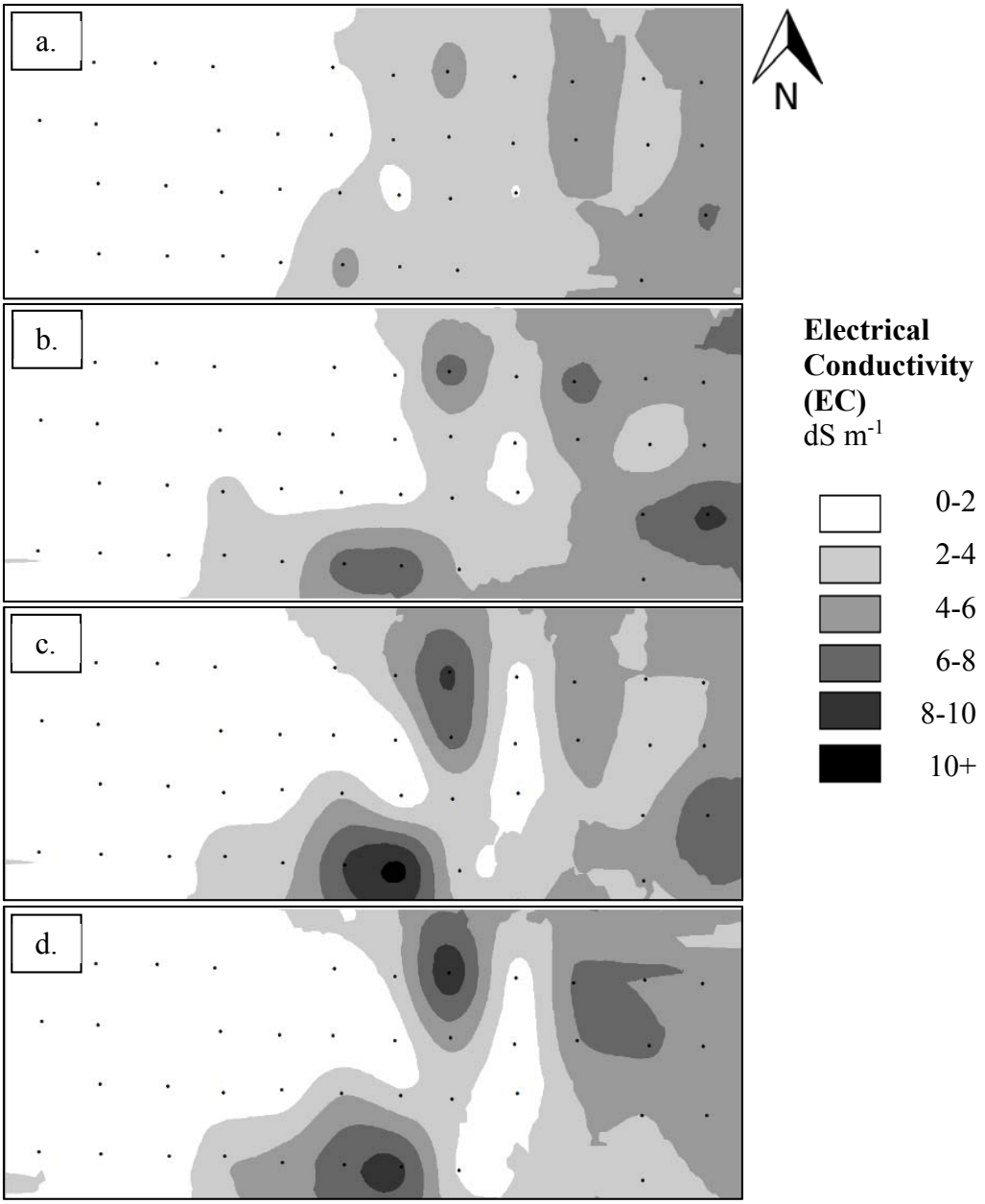

Figure 4.13. Electrical conductivity (EC) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Redfield*, SD samples. Untransformed data was interpolated using ordinary kriging.
*44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls [Soil Survey Division, 2014])

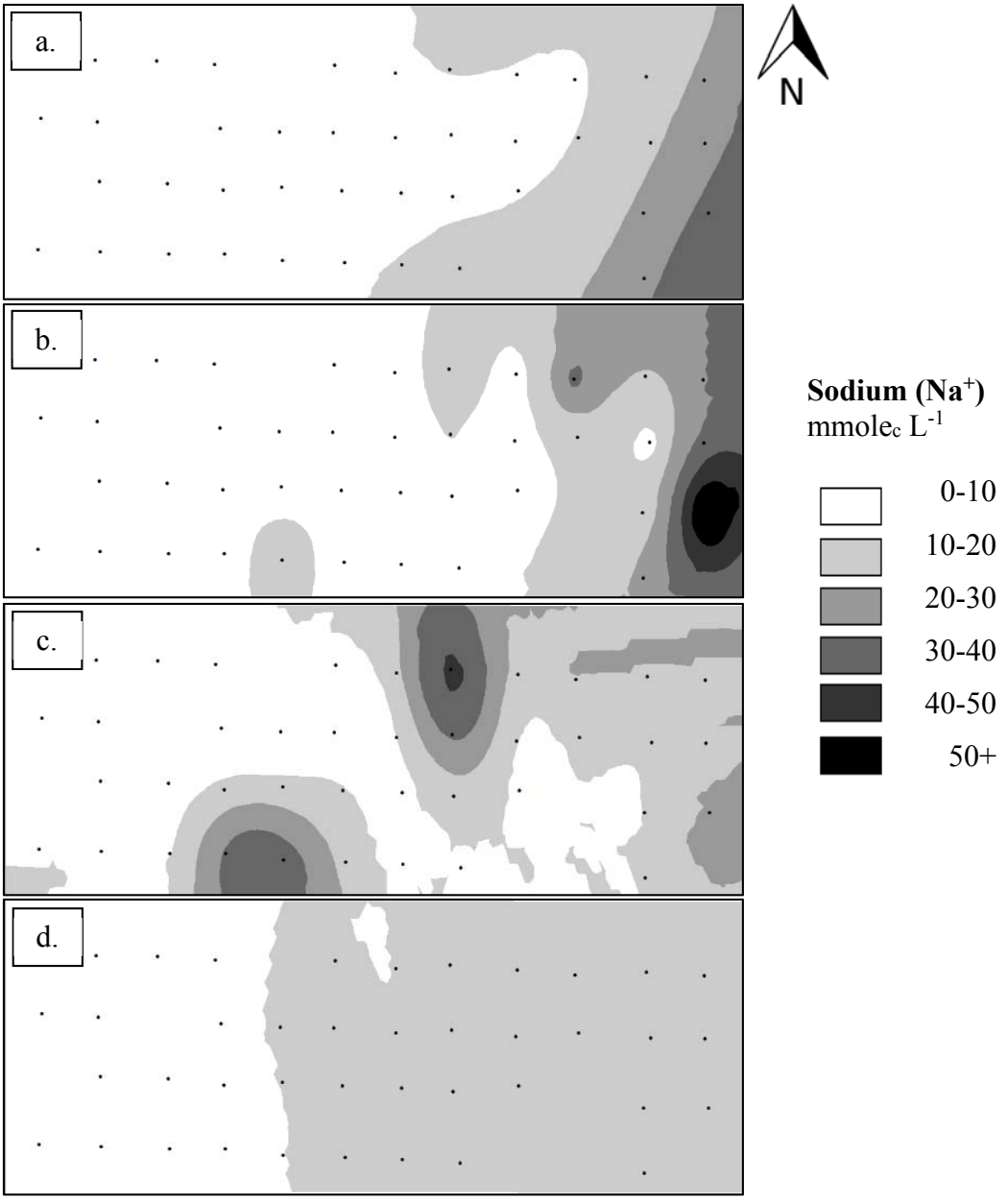

Figure 4.14. Sodium (Na^+) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Redfield*, SD samples. Untransformed data was interpolated using ordinary kriging.
*44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls [Soil Survey Division, 2014])

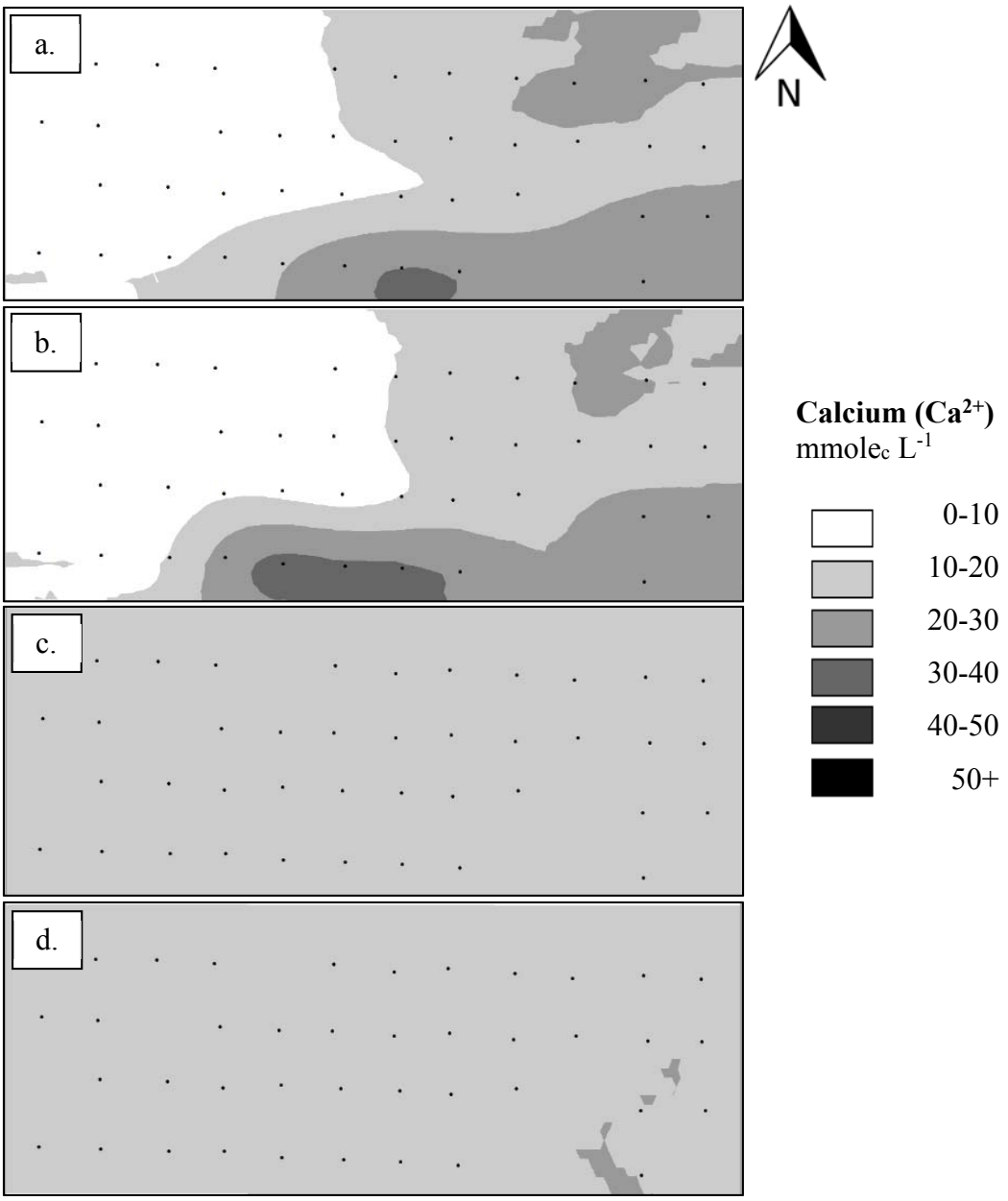

Figure 4.15. Calcium (Ca^{2+}) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Redfield*, SD samples. Untransformed data was interpolated using ordinary kriging.
*44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls [Soil Survey Division, 2014])

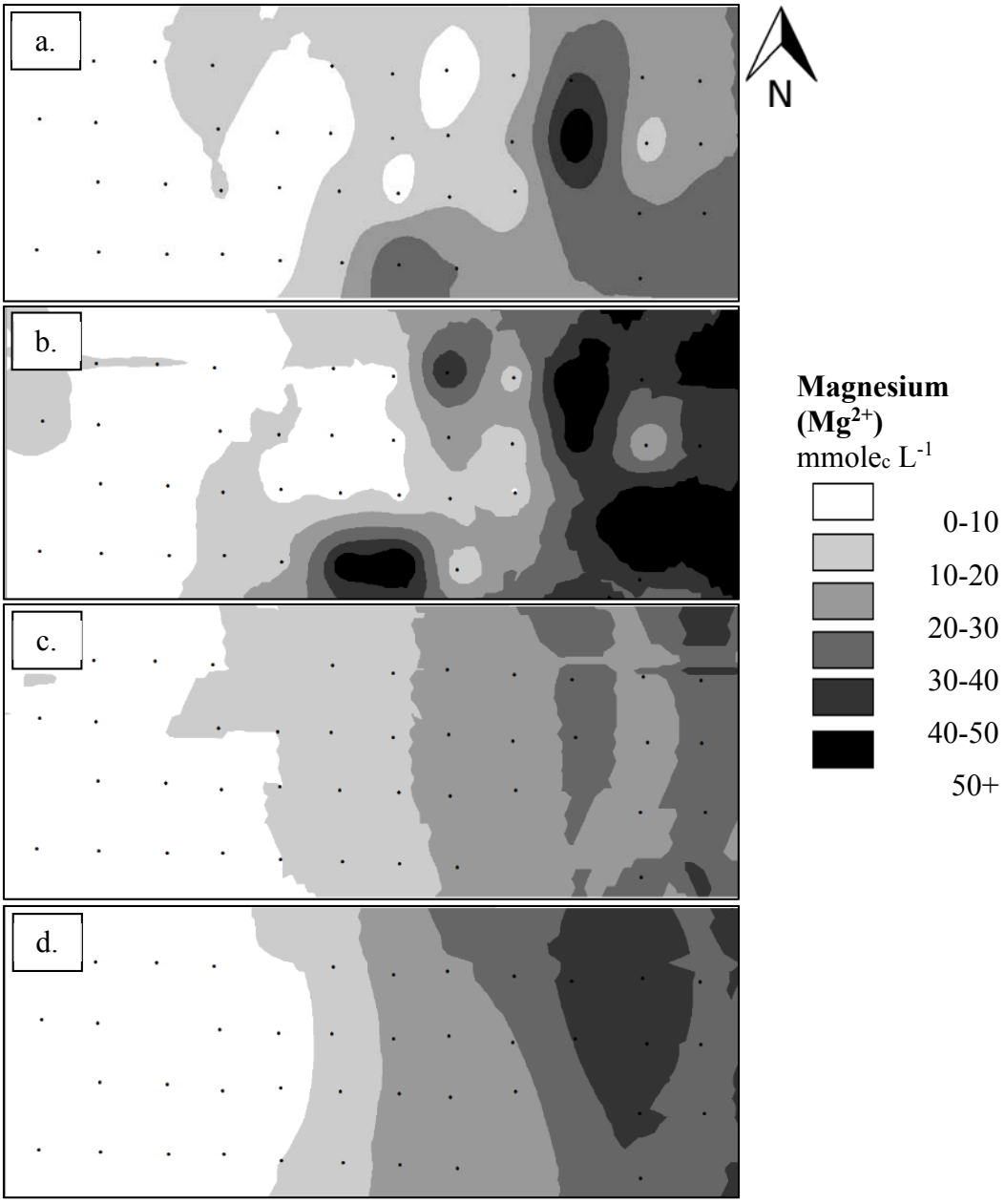

Figure 4.16. Magnesium (Mg^{2+}) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Redfield*, SD samples. Untransformed data was interpolated using ordinary kriging.
*44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls [Soil Survey Division, 2014])

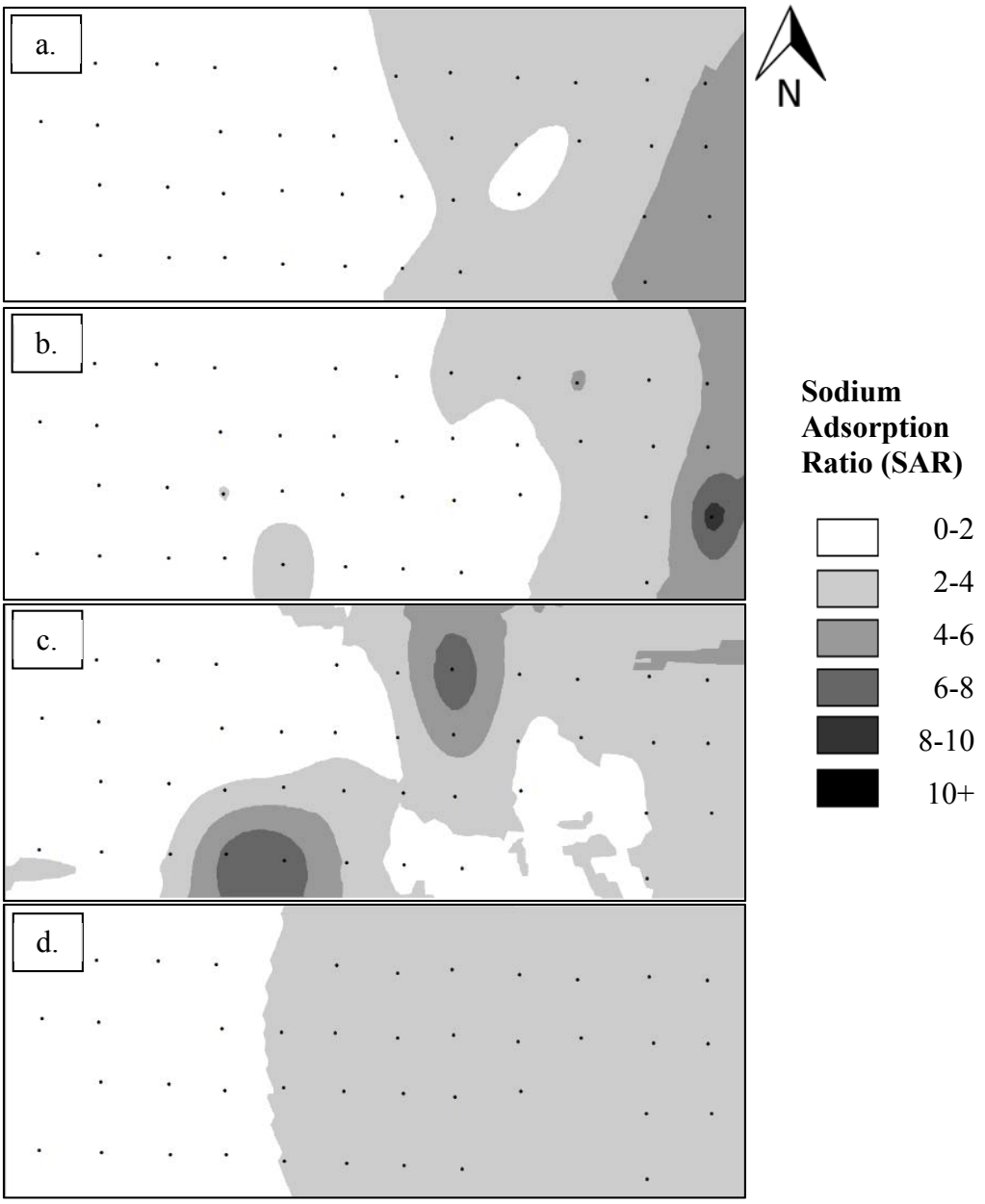

Figure 4.17. Sodium adsorption ratio (SAR) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Redfield*, SD samples. Untransformed data was interpolated using ordinary kriging.
*44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls [Soil Survey Division, 2014])

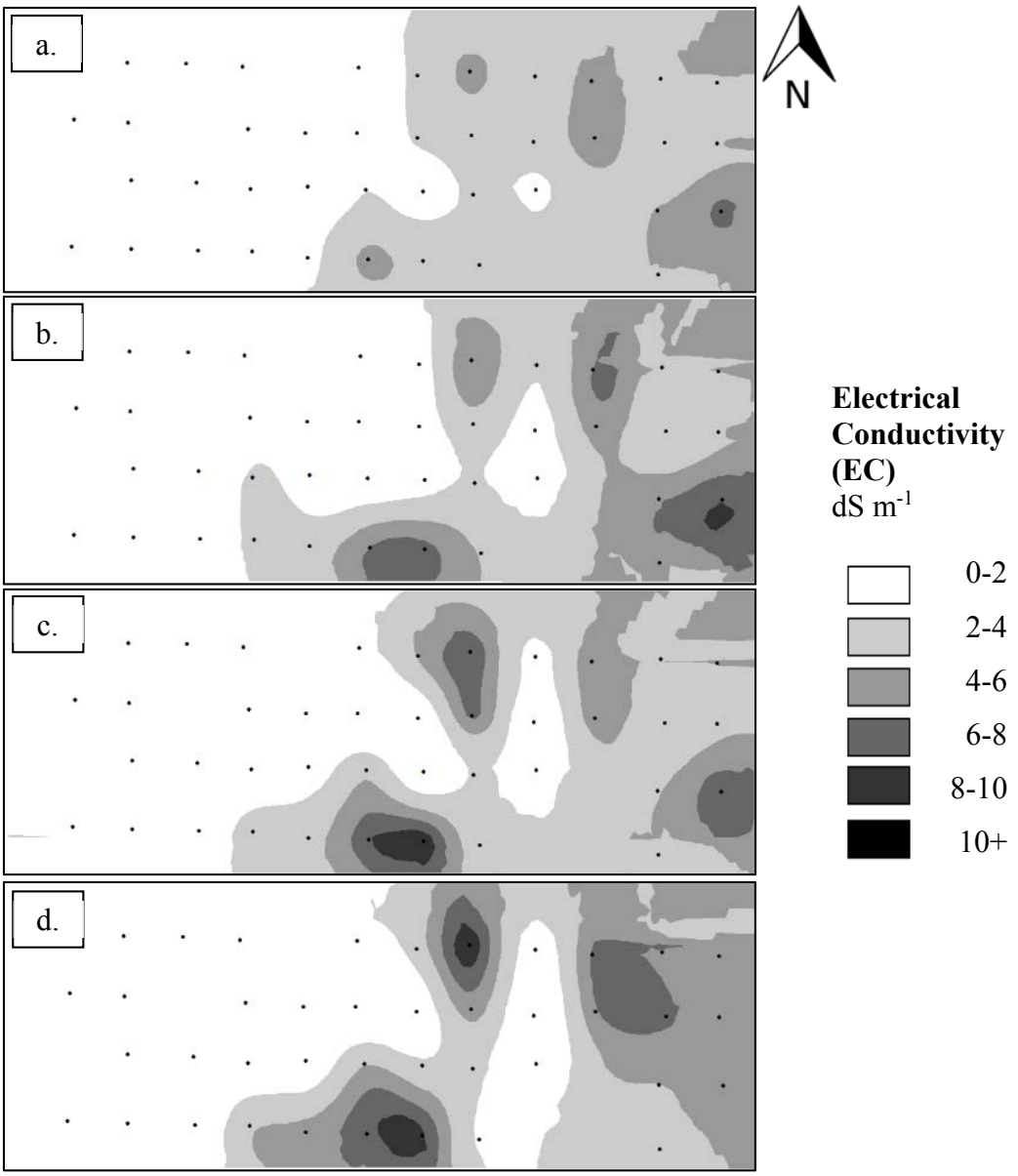

Figure 4.18. Electrical conductivity (EC) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Redfield*, SD samples. Log-transformed data was interpolated using ordinary kriging.
*44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls [Soil Survey Division, 2014])

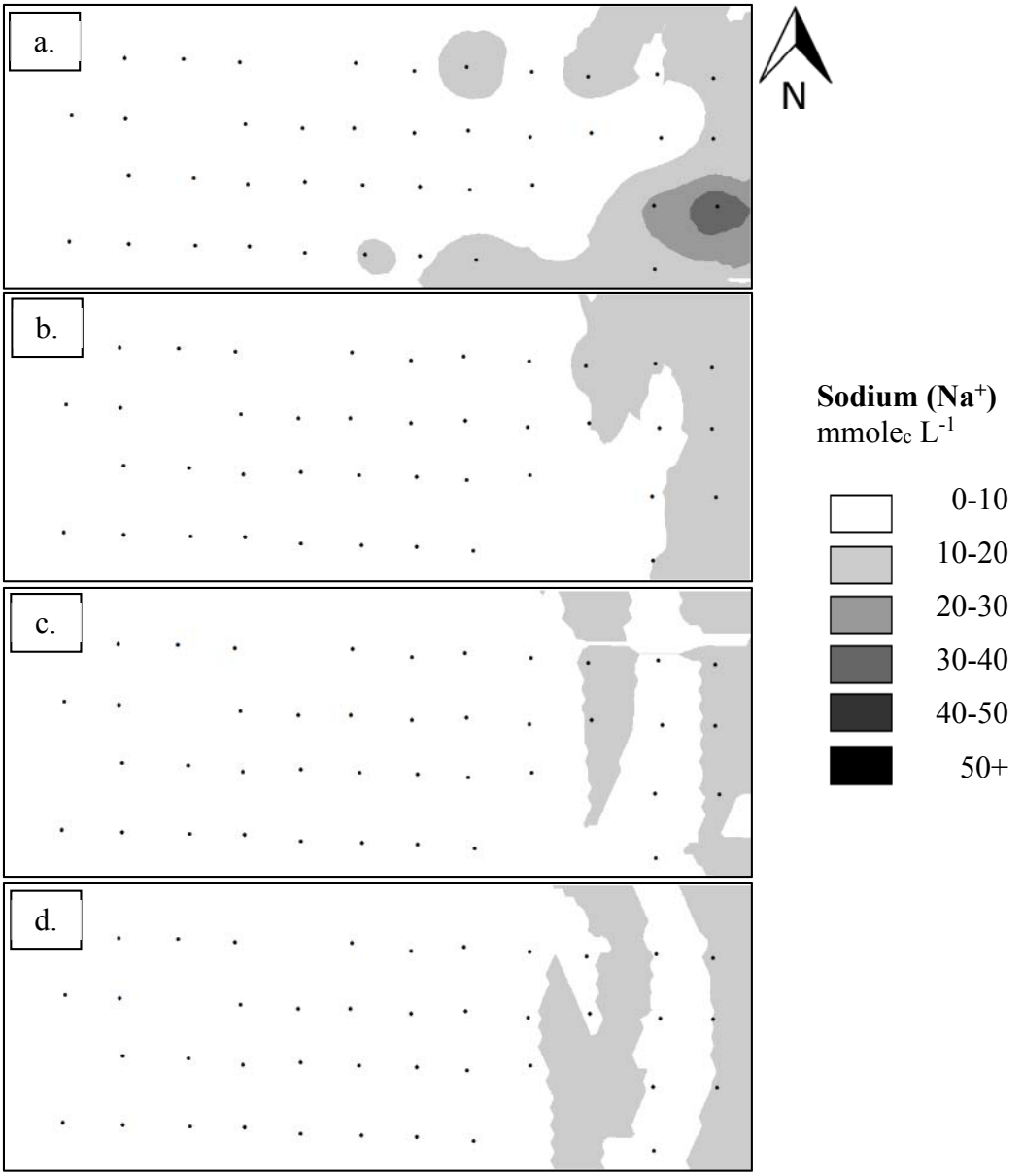

Figure 4.19. Sodium (Na^+) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Redfield*, SD samples. Log-transformed data was interpolated using ordinary kriging.
*44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls [Soil Survey Division, 2014])

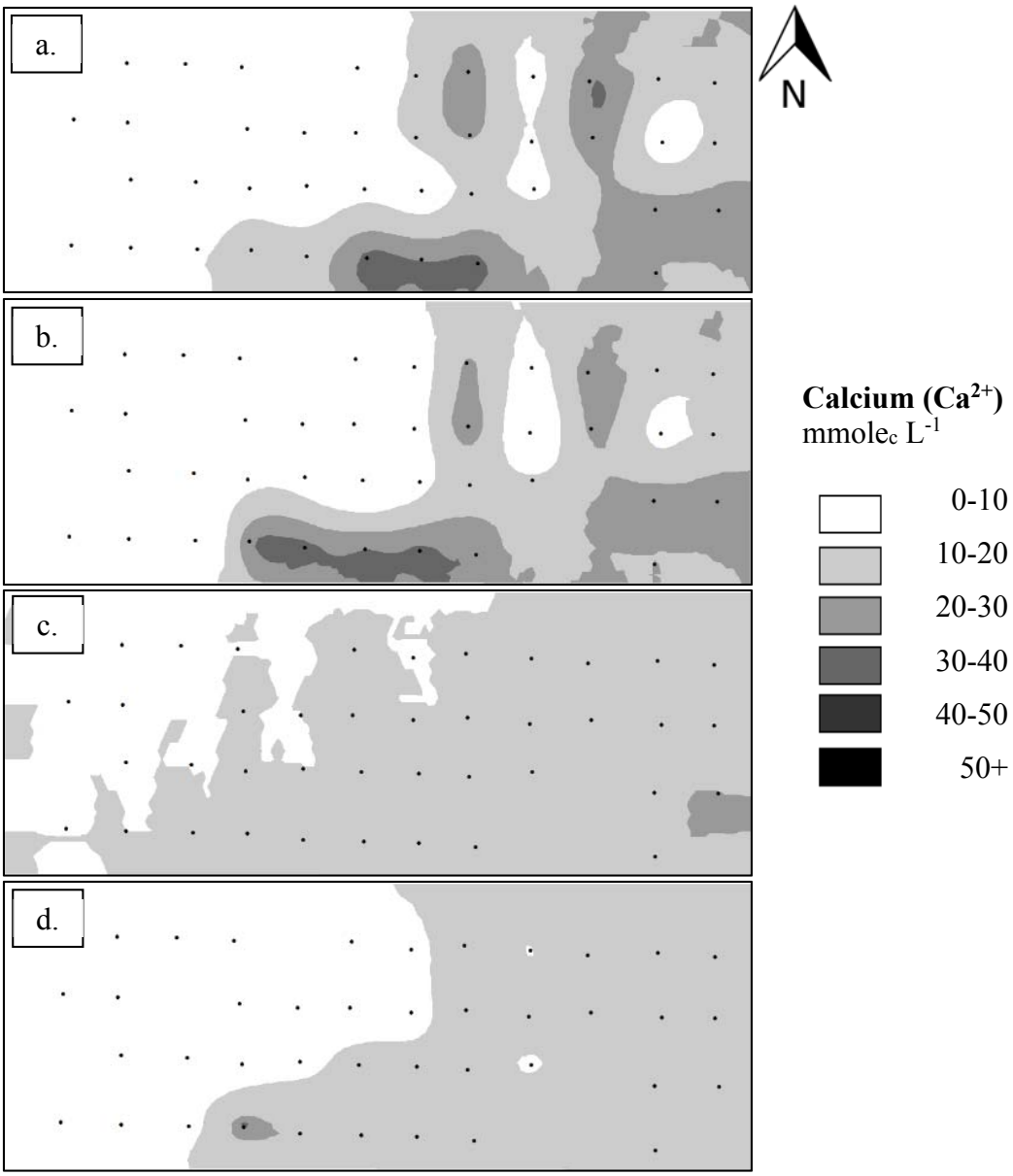

Figure 4.20. Calcium (Ca^{2+}) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Redfield*, SD samples. Log-transformed data was interpolated using ordinary kriging.
*44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls [Soil Survey Division, 2014])

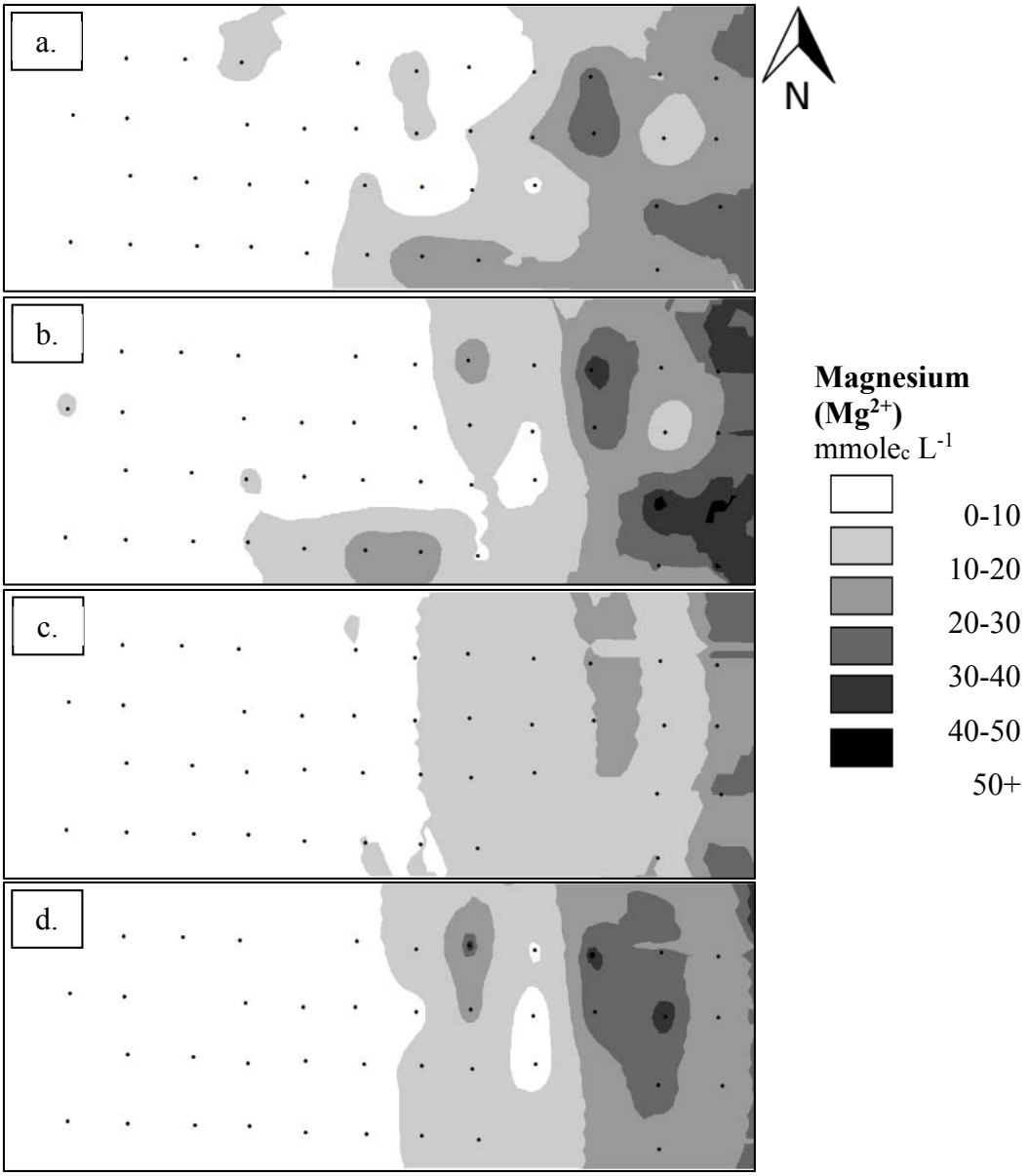

Figure 4.21. Magnesium (Mg^{2+}) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Redfield*, SD samples. Log-transformed data was interpolated using ordinary kriging.
*44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls [Soil Survey Division, 2014])

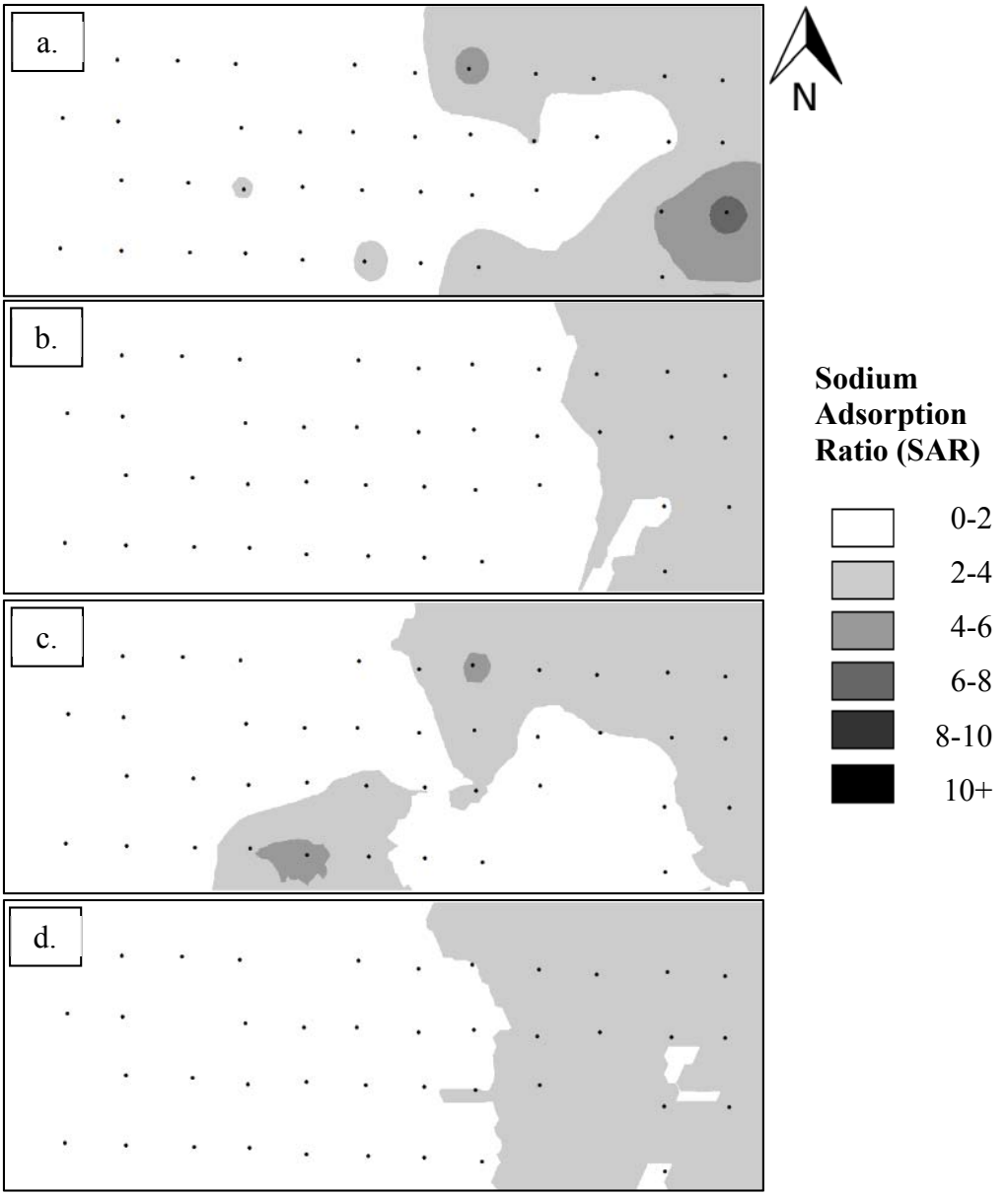

Figure 4.22. Sodium adsorption ratio (SAR) distribution for a. 0-7.5 cm, b. 7.5-15 cm, c. 15-30 cm, and d. 30-60 cm for Redfield*, SD samples. Log-transformed data was interpolated using ordinary kriging.
*44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls [Soil Survey Division, 2014])

Table 4.1. Soil classification, slope, and parent material information for Day County, South Dakota soil samples. Samples were collected near Pierpont*, South Dakota in November 2013 following soybean (*Glycine max* L.) harvest.

Map Unit Symbol	Series**	Slope (%)	Taxonomic Classification***	Parent Material
G102A	Hamerly loam	0-3	Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls	Fine-loamy till
G190C	Forman-Buse-Aastad loams	3-9	Fine-loamy, mixed, superactive, frigid Calcic Argiudolls Fine-loamy, mixed, superactive, frigid Typic Calciudolls Fine-loamy, mixed, superactive, frigid Pachic Argiudolls	Fine-loamy till
G543A	Playmoor silty clay loam	0-2	Fine-silty, mixed, superactive, calcareous, frigid Cumulic Endoaquolls	Silty alluvium
G790A	Kranzburg-Brookings silt loams	0-2	Fine-silty, mixed, superactive, frigid Calcic Hapludolls Fine-silty, mixed, superactive, frigid Pachic Hapludolls	Silty loess over fine-loamy till
G790B	Kranzburg-Brookings silt loams	2-6	Fine-silty, mixed, superactive, frigid Calcic Hapludolls Fine-silty, mixed, superactive, frigid Pachic Hapludolls	Silty loess over fine-loamy till
G792B	Kranzburg-Brookings-Buse complex	0-6	Fine-silty, mixed, superactive, frigid Calcic Hapludolls Fine-silty, mixed, superactive, frigid Pachic Hapludolls Fine-loamy, mixed, superactive, frigid Typic Calciudolls	Silty loess over fine-loamy till
G852A	Nahon-Aberdeen-Exline silt loams	0-2	Fine, smectitic, frigid Calcic Natrudolls Fine, smectitic, frigid Glossic Natrudolls Fine, smectitic, frigid Leptic Natrudolls	Silty and clayey glaciolacustrine deposits over fine-loamy till
G862A	Harmony-Beotia silt loams	0-2	Fine, smectitic, frigid Pachic Argiudolls Fine-silty, mixed, superactive, frigid Pachic Hapludolls	Silty and clayey glaciolacustrine deposits

*45.4751° N, 97.8359° W
**(NRCS, 2014b)
***(Soil Survey Division, 2014)

Table 4.2. Soil classification, slope, and parent material information for Spink County, South Dakota soil samples. Samples were collected near Redfield*, South Dakota in June and July 2013 following corn (*Zea mays* L.) planting.

Map Unit Symbol	Series**	Slope (%)	Taxonomic Classification***	Parent Material
G720A	Great Bend-Beotia silt loams	0-2	Fine-silty, mixed, superactive, frigid Calcic Hapludolls Fine-silty, mixed, superactive, frigid Pachic Hapludolls	Fine-silty glaciolacustrine deposits
G722B	Great Bend-Zell silt loams	2-6	Fine-silty, mixed, superactive, frigid Calcic Hapludolls Coarse-silty, mixed, superactive frigid Typic Calciudolls	Fine-silty glaciolacustrine deposits
G866A	Harmony-Aberdeen silty clay loams	0-2	Fine, smectitic, frigid Pachic Argiudolls Fine, smectitic, frigid Glossic Natrudolls	Silty and clayey glaciolacustrine deposits
G868A	Winship-Tonka silt loams	0-1	Fine-silty, mixed, superactive, frigid Pachic Argiudolls Fine, smectitic, frigid Argiaquic Argialbolls	Fine silty-glaciolacustrine deposits

*44.9250° N, 97.4760° W
**(NRCS, 2014b)
***(Soil Survey Division, 2014)

Table 4.3. Soil test data for non-transformed Pierpont*, SD samples (n = 203).

Soil Property	Depth (cm)	Pierpont* Mean	Median	StDev	Max	Min	CV†	Skewness	Kurtosis	Pr < W
EC ($dS\ m^{-1}$)	0-7.5	7.07	2.79	9.86	42.1	0.14	140	1.75	1.79	< 0.01
	7.5-15	5.39	3.19	5.69	22.1	0.12	106	1.32	0.60	< 0.01
	15-30	5.19	3.40	5.16	2.9	0.13	99	1.21	0.42	< 0.01
	30-60	5.09	2.96	4.94	21.1	0.18	97	1.30	0.74	< 0.01
Na^+ ($mmole_c\ L^{-1}$)	0-7.5	31.1	8.75	53.3	260	0	171	2.52	6.30	< 0.01
	7.5-15	24.9	9.03	40.7	403	0	163	4.75	37.2	< 0.01
	15-30	21.3	8.00	28.6	140	0	135	1.82	2.94	< 0.01
	30-60	21.2	8.00	27.6	145	0.21	130	2.00	3.97	< 0.01
Ca^{2+} ($mmole_c\ L^{-1}$)	0-7.5	17.7	15.4	11.6	56.2	0	66	0.41	-0.78	< 0.01
	7.5-15	22.5	21.0	29.5	231	0	131	4.79	26.7	< 0.01
	15-30	23.2	22.4	28.5	217	0.68	122	4.57	25.0	< 0.01
	30-60	23.2	20.7	26.9	218	0.50	116	4.49	25.0	< 0.01
Mg^{2+} ($mmole_c\ L^{-1}$)	0-7.5	65.6	15.0	122	608	0	186	2.55	6.11	< 0.01
	7.5-15	45.8	14.4	66.5	269	0	145	1.80	2.21	< 0.01
	15-30	45.0	14.4	61.3	252	0	136	1.60	1.38	< 0.01
	30-60	44.1	15.0	59.5	225	0	135	1.66	1.56	< 0.01
SAR	0-7.5	3.98	2.26	5.51	42.9	0	139	3.51	17.58	< 0.01
	7.5-15	3.83	2.42	4.94	35.9	0	129	3.36	15.2	< 0.01
	15-30	3.12	2.12	3.13	14.8	0	100	1.48	2.09	< 0.01
	30-60	3.28	2.19	3.11	15.19	0.07	95	1.66	2.83	< 0.01

*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls [Soil Survey Division, 2014])

†CV = Coefficient of Variation; Skewness describes data deviation left of right of the mean from a normal distribution; Kurtosis describes the peakedness or flatness of the data; Pr < W is the Shapiro-Wilk probability level for test of normality (<0.05 indicates non-normality).

Table 4.4. Soil test data for non-transformed Redfield*, SD samples (n = 41).

Soil Property	Depth (cm)	Redfield* Mean	Median	StDev	Max	Min	CV†	Skewness	Kurtosis	Pr < W
EC ($dS\ m^{-1}$)	0-7.5	2.49	1.74	2.11	10.0	0.44	85	1.71	3.09	< 0.01
	7.5-15	2.57	1.11	2.76	8.98	0.28	107	1.27	0.13	< 0.01
	15-30	2.78	1.52	2.74	10.4	0.25	99	1.29	0.64	< 0.01
	30-60	2.93	1.77	2.53	9.40	0.31	87	0.90	-0.30	< 0.01
Na^+ ($mmole_c\ L^{-1}$)	0-7.5	7.67	4.49	10.2	46.7	0	132	2.39	5.97	< 0.01
	7.5-15	7.86	2.93	14.1	76.0	0.46	179	3.48	14.03	< 0.01
	15-30	11.8	4.57	17.7	75.1	0.21	150	2.28	4.70	< 0.01
	30-60	12.7	3.85	20.0	108	0.45	157	3.14	12.36	< 0.01
Ca^{2+} ($mmole_c\ L^{-1}$)	0-7.5	13.5	8.38	10.0	35.8	2.47	74	0.93	-0.61	< 0.01
	7.5-15	14.2	7.48	12.0	35.2	1.67	84	0.68	-1.33	< 0.01
	15-30	14.7	8.60	13.5	67.3	3.54	92	1.79	4.34	< 0.01
	30-60	15.9	6.67	18.9	113.8	3.36	119	3.63	17.8	< 0.01
Mg^{2+} ($mmole_c\ L^{-1}$)	0-7.5	16.7	10.2	21.1	110	1.34	126	2.85	9.58	< 0.01
	7.5-15	20.8	6.04	28.2	90.3	0.70	135	1.43	0.47	< 0.01
	15-30	15.3	6.77	18.0	67.1	0.46	118	1.65	1.84	< 0.01
	30-60	18.5	5.80	23.4	75.2	0	126	1.44	0.62	< 0.01
SAR	0-7.5	1.75	1.42	1.72	8.28	0	98	2.12	5.32	< 0.01
	7.5-15	1.65	1.02	1.99	11.3	0.11	121	3.28	13.5	< 0.01
	15-30	2.54	1.52	2.94	11.3	0.11	116	1.95	3.23	< 0.01
	30-60	2.57	1.42	2.92	15.3	0.18	114	2.63	8.63	< 0.01

*44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls [Soil Survey Division, 2014])
†CV = Coefficient of Variation; Skewness describes data deviation right or left of the mean from a normal distribution; Kurtosis describes the peakedness or flatness of the data; Pr < W is the Shapiro-Wilk probability level for test of normality (<0.05 indicates non-normality).

Table 4.5. Soil test data for log-transformed Pierpont*, SD samples (n = 203).

Parameter	Depth (cm)	Pierpont* Mean	Median	StDev	Max	Min	CV†	Skewness	Kurtosis	Pr < W
lnEC ($dS\ m^{-1}$)	0-7.5	1.52	1.33	1.01	3.76	0.13	67	0.69	-0.62	< 0.01
	7.5-15	1.49	1.43	0.85	3.14	0.12	57	0.23	-0.98	< 0.01
	15-30	1.49	1.48	0.82	3.09	0.12	46	0.18	-1.06	< 0.01
	30-60	1.51	1.38	0.76	3.09	0.16	50	0.30	-0.96	< 0.01
$lnNa^{+}$ ($mmole_c\ L^{-1}$)	0-7.5	2.35	2.28	1.51	5.56	0.00	64	0.41	-0.94	< 0.01
	7.5-15	2.38	2.31	1.38	6.00	0.00	58	0.14	-0.98	< 0.01
	15-30	2.28	2.20	1.35	4.95	0.00	59	0.16	-1.14	< 0.01
	30-60	2.41	2.20	1.21	4.99	0.19	50	0.19	-0.98	< 0.01
$lnCa^{2+}$ ($mmole_c\ L^{-1}$)	0-7.5	2.68	2.80	0.79	4.05	0.00	29	-0.74	0.16	< 0.01
	7.5-15	2.75	3.09	0.90	5.45	0.00	33	-0.11	0.29	< 0.01
	15-30	2.82	3.15	0.85	5.39	0.52	30	0.03	0.02	< 0.01
	30-60	2.84	3.08	0.82	5.39	0.40	29	-0.02	0.39	< 0.01
$lnMg^{2+}$ ($mmole_c\ L^{-1}$)	0-7.5	2.87	2.77	1.64	6.41	0.00	57	0.40	-0.76	< 0.01
	7.5-15	2.79	2.73	1.56	5.60	0.00	56	0.07	-1.08	< 0.01
	15-30	2.87	2.74	1.48	5.53	0.00	52	0.07	-1.07	< 0.01
	30-60	2.96	2.77	1.36	5.42	0.00	46	0.16	-0.87	< 0.01
lnSAR	0-7.5	1.24	1.18	0.80	3.78	0.00	65	0.65	-0.22	< 0.01
	7.5-15	1.25	1.23	0.76	3.61	0.00	60	0.53	-0.10	< 0.01
	15-30	1.16	1.14	0.71	2.76	0.00	61	0.27	-0.97	< 0.01
	30-60	1.23	1.16	0.65	2.78	0.07	53	0.32	-0.68	< 0.01

*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls [Soil Survey Division, 2014])

†CV = Coefficient of Variation; Skewness describes data deviation right or left of the mean from a normal distribution; Kurtosis describes the peakedness or flatness of the data; Pr < W is the Shapiro-Wilk probability level for test of normality (<0.05 indicates non-normality).

Table 4.6. Soil test data for log-transformed Redfield*, SD samples (n = 41).

Parameter	Depth (cm)	Redfield* Mean	Median	StDev	Max	Min	CV†	Skewness	Kurtosis	Pr < W
lnEC ($dS\ m^{-1}$)	0-7.5	1.11	1.01	0.52	2.40	0.37	46	0.65	-0.32	0.05
	7.5-15	1.03	0.75	0.66	2.30	0.25	64	0.79	-0.85	< 0.01
	15-30	1.11	0.93	0.65	2.43	0.23	59	0.54	-0.95	0.01
	30-60	1.17	1.02	0.63	2.34	0.27	54	0.31	-1.38	< 0.01
$lnNa^{+}$ ($mmole_c\ L^{-1}$)	0-7.5	1.68	1.70	0.96	3.87	0.00	57	0.36	-0.33	0.34
	7.5-15	1.57	1.37	0.98	4.34	0.38	63	1.07	0.64	< 0.01
	15-30	1.87	1.72	1.13	4.33	0.19	61	0.53	-0.48	0.08
	30-60	1.94	1.58	1.13	4.69	0.37	59	0.55	-0.60	0.04
$lnCa^{2+}$ ($mmole_c\ L^{-1}$)	0-7.5	2.46	2.24	0.67	3.60	1.25	27	0.33	-1.14	0.01
	7.5-15	2.40	2.14	0.82	3.59	0.98	34	0.21	-1.37	< 0.01
	15-30	2.45	2.26	0.77	4.22	1.51	31	0.46	-1.11	< 0.01
	30-60	2.46	2.04	0.82	4.74	1.47	34	0.66	-0.50	< 0.01
$lnMg^{2+}$ ($mmole_c\ L^{-1}$)	0-7.5	2.41	2.42	0.95	4.71	0.85	39	0.30	-0.20	0.50
	7.5-15	2.32	1.95	1.23	4.51	0.53	53	0.58	-0.99	< 0.01
	15-30	2.27	2.05	1.02	4.22	0.38	45	0.37	-0.87	0.08
	30-60	2.31	1.92	1.16	4.33	0.00	50	0.37	-0.86	0.02
lnSAR	0-7.5	0.87	0.88	0.52	2.23	0.00	59	0.57	0.29	0.28
	7.5-15	0.82	0.70	0.51	2.51	0.11	63	1.24	1.88	< 0.01
	15-30	1.02	0.92	0.66	2.51	0.10	64	0.80	-0.03	0.01
	30-60	1.05	0.88	0.62	2.79	0.16	59	0.78	0.31	0.05

*44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls [Soil Survey Division, 2014])
†CV = Coefficient of Variation; Skewness describes data deviation right or left of the mean from a normal distribution; Kurtosis describes the peakedness or flatness of the data; Pr < W is the Shapiro-Wilk probability level for test of normality (<0.05 indicates non-normality).

Table 4.7. Precursory tests for spatial distribution of Pierpont*, SD (n = 203) and Redfield**, SD (n = 41) non-transformed soil sample parameters of electrical conductivity (EC), sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium adsorption ratio (SAR).

		Pierpont*			Redfield**		
Parameter	**Depth (cm)**	**Moran's I Value†**	**P-value**	**Angle of Ellipse (°)**	**Moran's I Value**	**P-value**	**Angle of Ellipse (°)**
EC	0-7.5	0.80	< 0.01	21.3	0.44	< 0.01	93.4
	7.5-15	0.73	< 0.01	18.9	0.52	< 0.01	90.2
	15-30	0.73	< 0.01	18.9	0.40	< 0.01	89.8
	30-60	0.76	< 0.01	20.6	0.41	0.01	85.3
Na^+	0-7.5	0.55	< 0.01	17.5	0.54	< 0.01	98.1
	7.5-15	0.34	< 0.01	20.4	0.11	0.30	94.9
	15-30	0.48	< 0.01	17.0	0.21	0.11	81.3
	30-60	0.43	< 0.01	18.9	0.00	0.82	90.6
Ca^{2+}	0-7.5	0.58	< 0.01	10.7	0.62	< 0.01	87.9
	7.5-15	0.06	0.08	2.40	0.40	0.01	90.5
	15-30	0.23	< 0.01	176	0.16	0.21	87.6
	30-60	0.16	< 0.01	14.1	0.07	0.42	81.7
Mg^{2+}	0-7.5	0.68	< 0.01	18.9	0.40	< 0.01	97.2
	7.5-15	0.59	< 0.01	14.9	0.52	< 0.01	92.0
	15-30	0.76	< 0.01	18.5	0.31	0.03	89.1
	30-60	0.78	< 0.01	18.5	0.19	0.17	89.9
SAR	0-7.5	0.34	< 0.01	21.2	0.39	< 0.01	96.1
	7.5-15	0.15	< 0.01	27.6	0.00	0.82	93.1
	15-30	0.26	< 0.01	21.2	0.20	0.14	84.2
	30-60	0.34	< 0.01	22.9	0.04	0.65	92.6

*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls)
**44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls[Soil Survey Division, 2014])
†Moran's I Value tests for spatial autocorrelation (Values > 0 indicate positive spatial autocorrelation); P-value shows probability for Moran's I value; Angle of Ellipse describes the directional distribution of the data (0-90° NE –SW; 90-180° NW-SE).

Table 4.8. Precursory tests for spatial distribution of Pierpont*, SD (n = 203) and Redfield**, SD (n = 41) log-transformed soil sample parameters of electrical conductivity (EC), sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium adsorption ratio (SAR).

		Pierpont*			Redfield**		
Parameter	**Depth (cm)**	**Moran's I Value†**	**P-value**	**Angle of Ellipse (°)**	**Moran's I Value**	**P-value**	**Angle of Ellipse (°)**
lnEC	0-7.5	0.80	< 0.01	19.0	0.56	< 0.01	91.6
	7.5-15	0.73	< 0.01	17.1	0.56	< 0.01	90.7
	15-30	0.75	< 0.01	16.0	0.47	< 0.01	90.2
	30-60	0.76	< 0.01	18.8	0.52	< 0.01	88.0
$lnNa^+$	0-7.5	0.68	< 0.01	17.7	0.53	< 0.01	93.6
	7.5-15	0.57	< 0.01	17.3	0.29	0.04	92.0
	15-30	0.54	< 0.01	15.4	0.29	0.05	88.3
	30-60	0.59	< 0.01	17.0	0.29	0.04	89.9
$lnCa^{2+}$	0-7.5	0.55	< 0.01	23.8	0.59	< 0.01	89.3
	7.5-15	0.32	< 0.01	20.9	0.31	0.04	90.7
	15-30	0.49	< 0.01	16.0	0.22	0.12	89.2
	30-60	0.42	< 0.01	25.2	0.32	0.03	88.3
$lnMg^{2+}$	0-7.5	0.73	< 0.01	21.0	0.52	< 0.01	92.7
	7.5-15	0.57	< 0.01	14.5	0.48	< 0.01	91.9
	15-30	0.64	< 0.01	18.3	0.31	0.04	89.9
	30-60	0.73	< 0.01	17.6	0.23	0.11	90.9
lnSAR	0-7.5	0.54	< 0.01	19.4	0.38	0.01	93.9
	7.5-15	0.40	< 0.01	20.2	0.07	0.55	91.5
	15-30	0.38	< 0.01	18.6	0.23	0.11	88.1
	30-60	0.41	< 0.01	18.1	0.22	0.13	90.6

*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls)
**44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls[Soil Survey Division, 2014])
†Moran's I Value tests for spatial autocorrelation (Values > 0 indicate positive spatial autocorrelation); P-value shows probability for Moran's I value; Angle of Ellipse describes the directional distribution of the data (0-90° NE –SW; 90-180° NW-SE).

Table 4.9. Spatial distribution characteristics determined using ordinary kriging for Pierpont*, SD (n = 203) and Redfield**, SD (n = 41) non-transformed soil sample parameters of electrical conductivity (EC), sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium adsorption ratio (SAR).

		Pierpont*					Redfield**				
Parameter	**Depth (cm)**	**a (m)†**	**C_0 (γ)**	**C (γ)**	**RMSE**	**R^2**	**a (m)**	**C_0 (γ)**	**C (γ)**	**RMSE**	**R^2**
EC	0-7.5	2.76	0.02	20.5	4.81	0.80	156	0	2.61	2.14	0.31
	7.5-15	30.2	6.59	15.1	2.77	0.75	153	0	7.13	2.03	0.42
	15-30	170	4.97	29.0	2.77	0.70	113	0	8.46	1.75	0.41
	30-60	30.9	3.85	10.4	2.54	0.74	113	0	6.91	1.55	0.55
Na^+	0-7.5	262	1110	2500	38.8	0.33	336	28.7	87.5	9.49	0.38
	7.5-15	350	196	662	56.6	0.39	192	0	143	14.2	0.13
	15-30	389	258	730	15.0	0.56	113	237	220	5.99	0.38
	30-60	33.1	213	691	18.3	0.57	194	186	0	31.2	0.15
Ca^{2+}	0-7.5	370	34.6	110	6.51	0.66	220	41.7	63.7	3.01	0.86
	7.5-15	39.6	12.7	55.1	37.4	0.12	170	54.6	107	12.3	0.05
	15-30	711	162	1170	20.0	0.49	276	201	0	9.71	0.35
	30-60	711	0	812	27.8	0.11	475	435	0	11.1	0.08
Mg^{2+}	0-7.5	29.4	8750	15000	44.7	0.80	224	0	268	25.2	0.41
	7.5-15	2.99	984	2310	45.1	0.48	169	0	733	25.8	0.27
	15-30	32.7	559	2500	27.6	0.57	172	326	0	15.4	0.44
	30-60	23.2	369	2420	26.1	0.78	222	369	175	19.7	0.22
SAR	0-7.5	99.3	22.8	18.8	3.93	0.26	264	1.46	1.95	1.55	0.26
	7.5-15	402	0	14.7	7.05	0.13	192	0	3.20	1.89	0.10
	15-30	69.5	4.54	6.08	2.11	0.34	113	6.09	6.11	1.61	0.23
	30-60	49.9	2.03	6.28	3.05	0.27	194	4.22	0	4.03	0.49

*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls)
**44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls[Soil Survey Division, 2014])
†a = lag distance of spatial dependence (range); C_0 = nugget semi-variance; C = partial sill semi-variance; RMSE = Root Mean Square Error; R^2 = coefficient of determination

Table 4.10. Spatial distribution characteristics determined using ordinary kriging for Pierpont*, SD (n = 203) and Redfield**, SD (n = 41) log-transformed soil sample parameters of electrical conductivity (EC), sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium adsorption ratio (SAR).

		Pierpont*					Redfield**				
Parameter	**Depth (cm)**	**a (m)†**	**C_0 (γ)**	**C (γ)**	**RMSE**	**R^2**	**a (m)**	**C_0 (γ)**	**C (γ)**	**RMSE**	**R^2**
lnEC	0-7.5	393	0	1.16	0.46	0.79	153	0.00	0.19	0.35	0.55
	7.5-15	711	0.03	0.97	0.44	0.74	113	0.08	0.31	0.50	0.48
	15-30	325	0.01	0.68	0.42	0.75	113	0.02	0.44	0.35	0.46
	30-60	433	0.01	0.64	0.37	0.78	113	0	0.39	0.40	0.61
$lnNa^+$	0-7.5	707	0	3.04	0.93	0.61	176	0	0.80	0.71	0.31
	7.5-15	23.6	0.29	0	1.04	0.54	192	0	0.80	0.94	0.27
	15-30	711	0.20	2.20	0.83	0.59	177	1.40	0	0.52	0.69
	30-60	711	0.18	1.74	0.76	0.61	194	0.99	0	1.00	0.64
$lnCa^{2+}$	0-7.5	385	0.04	0.57	0.54	0.56	113	0.03	0.34	0.27	0.80
	7.5-15	57.2	0.02	0.31	0.71	0.43	113	0.08	0.63	0.87	0.03
	15-30	711	0.06	0.93	0.51	0.64	164	0.63	0	0.63	0.26
	30-60	52.5	0	0.23	0.71	0.36	444	0	0.81	0.55	0.58
$lnMg^{2+}$	0-7.5	143	0.44	2.58	0.86	0.70	187	0	0.81	0.71	0.41
	7.5-15	405	0.59	2.00	1.20	0.42	178	0.36	1.09	0.99	0.50
	15-30	711	0	2.87	0.96	0.60	183	0.98	0	0.71	0.52
	30-60	405	0.05	1.92	0.78	0.66	222	0	1.30	0.96	0.30
lnSAR	0-7.5	699	0	0.80	0.58	0.46	262	0	0.30	0.40	0.23
	7.5-15	23.6	0.08	0.07	0.73	0.34	192	0	0.23	0.48	0.23
	15-30	2.21	0.09	0.06	0.47	0.49	118	0.30	0.22	0.39	0.58
	30-60	711	0.09	0.40	0.53	0.41	194	0.28	0	0.66	0.58

*45.4751° N, 97.8359° W (Dominant soils: Calciaquolls, Argiudolls, Calciudolls, Endoaquolls, Hapludolls, Natrudolls)
**44.9250° N, 97.4760° W (Dominant soils: Hapludolls, Calciudolls, Argiudolls, Natrudolls, Argialbolls[Soil Survey Division, 2014])
†a = lag distance of spatial dependence (range); C_0 = nugget semi-variance; C = partial sill semi-variance; RMSE = Root Mean Square Error; R^2 = coefficient of determination

REFERENCES

Akramkhanov, A., D.J. Brus and D.J.J. Walvoort. 2014. Geostatistical monitoring of soil salinity in Uzbekistan by repeated EMI surveys. Geoderma 213: 600-607.

Aldabaa, A.A.A., D.C. Weindorf, S. Chakraborty, A. Sharma and B. Li. 2015. Combination of proximal and remote sensing methods for rapid soil salinity quantification. Geoderma 239-240: 34-46.

Corwin, D.L., S.R. Kaffka, J.W. Hopmans, Y. Mori, J.W. van Groenigen, C. van Kessel, et al. 2003. Assessment and field-scale mapping of soil quality properties of a saline-sodic soil. Geoderma 114: 231-259.

Daniels, R.D. 1987. Saline seeps in the Northern Great Plains of the USA and the Southern Prairies of Canada. In: M. G. Wolman and F. G. A. Fournier, editors, Land Transformation in Agriculture. John Wiley & Sons Ltd.

DeSutter, T.M. 2008. Problems in production fields: Saline and sodic soils. In: S. L. e. al., editor Soil science: step-by-step field analysis. . Soil Science Society of America Special Publication, Madison, WI. p. 183-200.

Douaik, A., M. Van Meirvenne and T. Tóth. 2005. Soil salinity mapping using spatio-temporal kriging and Bayesian maximum entropy with interval soft data. Geoderma 128: 234-248.

Franzen, D. 2007. Managing Saline Soils in North Dakota. NDSU Extension Service. file:///C:/Users/Owner/Downloads/Saline%20and%20Sodic%20Soils%20%20(1).pdf (accessed 28 Dec. 2014).

Ganjegunte, G.K. and R.J. Braun. 2011. Delineating Salinity and Sodicity Distribution in Major Soil Map Units of El Paso, Texas, Using Electromagnetic Induction Technique. Soil Science 176: 441-447.

Guo, Y., Z. Shi, H.Y. Li and J. Triantafilis. 2013. Application of digital soil mapping methods for identifying salinity management classes based on a study on coastal central China. Soil Use and Management 29: 445-456.

King, K.W., M.R. Williams, M.L. Macrae, N.R. Fausey, J. Frankenberger, D.R. Smith, et al. 2014. Phosphorus Transport in Agricultural Subsurface Drainage: A Review. Journal of Environment Quality: 0.

Li, H.Y., Z. Shi, R. Webster and J. Triantafilis. 2013. Mapping the three-dimensional variation of soil salinity in a rice-paddy soil. Geoderma 195-196: 31-41.

Li, H.Y., R. Webster and Z. Shi. 2015. Mapping soil salinity in the Yangtze delta: REML and universal kriging (E-BLUP) revisited. Geoderma 237-238: 71-77.

Liu, Q., W.J. Xie and J.B. Xia. 2013. Using Semivariogram and Moran's I Techniques to Evaluate Spatial Distribution of Soil Micronutrients. Communications in Soil Science and Plant Analysis 44: 1182-1192.

Mbonimpa, E.G., C.O. Hong, V.N. Owens, R.M. Lehman, S.L. Osborne, T.E. Schumacher, et al. 2014. Nitrogen fertilizer and landscape position impacts on CO2and CH4fluxes from a landscape seeded to switchgrass. GCB Bioenergy: n/a-n/a.

National Soil Survey Center. 1996. Soil Survey Methods Laboratory Manual USDA-NRCS.

NRCS. 2014. Major Land Resource Area Explorer. USDA-NRCS, http://apps.cei.psu.edu/mlra/ (accessed 01 Dec. 2014).

NRCS. 2014. Web Soil Survey. USDA-NRCS, http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx (accessed 01 Dec. 2014).

Nielsen, D.R. and O. Wendroth. 2003. Spatial and Temporal Statistics: Sampling Field Soils and their VegetationCatena Verlag GMBH, Reiskirchen, Germany.

Provin, T. and J.L. Pitt. 2012. Managing Soil Salinity. Texas A&M Agrilife Extension Service E-60. http://soiltesting.tamu.edu/publications/E-60.pdf. (accessed 28 Dec. 2014).

Rhoades, J.D. 1982. Soluble Salts. Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties. ASA-SSSA, Madison, WI.

Rhoades, J.D., S.M. Lesch, P.J. Shouse and W.J. Alves. 1990. Locating Sampling Sites for Salinity Mapping. Soil Sci. Soc. Am. J. 54: 1799-1803.

Soil Survey Division. 2014. Official Soil Series Descriptions. USDA-NRCS, https://soilseries.sc.egov.usda.gov/osdname.asp (accessed 01 Dec. 2014).

Taghizadeh-Mehrjardi, R., B. Minasny, F. Sarmadian and B.P. Malone. 2014. Digital mapping of soil salinity in Ardakan region, central Iran. Geoderma 213: 15-28.

US Salinity Laboratory Staff. 1954. Diagnosis and Improvement of Saline and Alkali Soils. In: L. Richards, editor Agricultural Handbook 60. USDA, Riverside, CA.

Yang, M., S.L. Liu, Z.F. Yang, T. Sun and R. Beazley. 2009. Multivariate and geostatistical analysis of wetland soil salinity in nested areas of the Yellow River Delta. Australian Journal of Soil Research 47: 486-497.

CHAPTER 5

CONCLUSIONS

The goal of Chapter 2 was to establish a relationship between electrical conductivity (EC) and the total soluble cations (TSC) in order to reduce the soil analysis needed to diagnose saline and sodic soils. Specifically, if EC can accurately predict TSC, researchers and soil testing laboratories can calculate the sodium adsorption ratio (SAR) using only EC and Na^+, eliminating the need to analyze for Ca^{2+} and Mg^{2+}. Previously developed models are not suited for soils affected by groundwater salinity in the Northern Great Plains, and a new, easy-to-use model is needed. Based on the results of this study, a linear model of TSC = 13.54*EC -0.29 is suited for the Northern Great Plains region (MLRA 55B and 55C) over all values of EC and can be applied with accuracy to saturated paste extractions analyzed for EC.

Chapter 3 aimed to establish relationships between saturated paste extractions, 1:1 soil to water extractions, and 1:5 soil to water extractions for various saline and sodic soil characteristics. In doing so, this study created a new methodology for soil testing labs in the Northern Great Plains to reduce confusion for producers interpreting saline and sodic soil test results. Results showed that all of the relationships analyzed were considered significant with p-values < 0.01, but the reliability of the prediction models varied based on the parameter of interest. Dilute extractions for Mg^{2+} were the best suited models, followed by EC, Na^+, SAR, and Ca^{2+} in decreasing order.

As Na^+ becomes increasingly important in the Northern Great Plains region and in soils affected by groundwater salinity, it is crucial for producers to consider both EC and SAR (or other measures of Na^+) when making management decisions. With current

practices, producers are advised to manage sodic soils using SAR values, but their soil test results are reported as a Na^+ percentage of base saturation, causing confusion in interpretation. If soil testing labs could use the 1:1 and 1:5 soil to water extractions to determine soluble cation concentrations, they would not need to make a saturated paste extraction to accurately predict SAR, saving time and costs. Based on results from this study, it is possible to create a prediction model for SAR_e using $SAR_{1:1}$ and $SAR_{1:5}$. Producers should consider managing for Na^+ below the currently recommended level of SAR > 13 due to high variability in the test results and the potential effect of the soluble Mg^{2+}.

Based on the results of this study, not only can linear regression relationships be developed between saturated paste extractions and various soil:water dilutions, but a non-linear relationship can also be established to predict the salinity parameters based on the dilution factor. Using this non-linear relationship for EC, Na^+, Ca^{2+}, Mg^{2+}, or SAR would allow any dilution results to be converted to any other dilution, including a saturated paste extraction. Soil texture should be taken into account when determining the dilution factor of the saturated paste extraction.

Finally, it is important to understand the spatial distribution of saline and sodic soil properties in order for farmers in Eastern South Dakota to better manage salt-affected areas in their fields, due to the adverse effects of soil salts on crop yield and soil health. The origin of soil salts in the Northern Great Plains differs from that of most saline and sodic soils studied, so research is needed to characterize these soils. The objective of Chapter 4 was to determine the field scale spatial distribution of EC, Na^+, Ca^{2+}, Mg^{2+},

and SAR at two field sites in Eastern South Dakota, where row crop production has been increasingly affected by saline and sodic soils.

Statistically, the soil test data in this study was highly variable for all parameters, which was likely caused by the tendency of saline and sodic soil properties to be distributed in hot spots. Using a log-transformation lowered the CV values for the data, but very few of the parameters were normally distributed, even after the transformation. Spatial distribution models are best fit for normally distributed data, so the heterogeneity of the data set limited the prediction accuracy. All data was positively spatially autocorrelated, so ordinary kriging was chosen as the method for creating prediction maps.

Statistical results for the semi-variograms were inconsistent for the soil test parameters, but some important overall trends were seen in the prediction maps. For many of the soil maps, using both non-transformed and log-transformed data and at both locations, saline and sodic soil properties were most severe in the top 7.5 cm of the soil, but with depth, the salt-affected area increased in size. The salts present from 30-60 cm may not be affecting crop production currently, but may be transported closer to the surface through capillary water flow and rising groundwater. Therefore, soils with subsurface salinity and sodicity should be identified and considered high risk. Future work should be done to develop better models to predict subsurface salt distribution. In addition to the spatial distribution of saline and sodic soil properties, it would also be beneficial to study how the distribution changes temporally.

APPENDICES

APPENDIX I: SOIL TESTING LAB SURVEY RESULTS

Testing Lab	Location	EC†	Cation Concentration‡	Sodium Index†‡
Iowa State University	Ames, IA	SP	NH_4OAc	SAR*
North Dakota State University	Fargo, ND	1:1	NH_4OAc	SAR
University of Minnesota	St. Paul, MN	1:1	NH_4OAc	SAR
AgLab Express	Sioux Falls, SD	1:1	NH_4OAc	ESP
AgVise Laboratory	Northwood, ND	1:1	NH_4OAc	ESP
Minnesota Valley Testing Lab	New Ulm, MN	1:1	NH_4OAc	ESP
Ward Laboratories	Kearney, NE	1:1	NH_4OAc	ESP
ServiTech	Hastings, NE	1:1	NH_4OAc	SAR*

†EC: Electrical Conductivity – SP: saturated paste extraction, 1:1: 1:1 soil to water (w/w) extraction

‡NH_4OAc: ammonium acetate extraction for exchangeable cations

†‡SAR: Sodium Adsorption Ratio, ESP: Exchangeable sodium percentage calculated from NH_4OAc extraction

*only available upon request

APPENDIX II: SAS CODE FOR LINEAR REGRESSION

```
/*ods trace on;
proc reg data=n1;
model EC=Tsalt/clb;
run;
ods trace off;*/

ods output FitStatistics=RSq ParameterEstimates=PEs;
proc reg data=n1;
model TSC=EC_L/clb;
run;
ods output close;

data ab;set pes;
id+1;
run;

data rs;set rsq;
id+1;
run;

data fina1;merge ab rs;
by id;
run;

data n1_r;set fina1;
drop model DF id label1 cvalue1 nvalue1 nvalue2;run;

proc export data=n1_r
  outfile='F:\A_LAB\Ra\n1_results.csv'
  dbms=csv
  replace;
run;

/*proc contents data=rsq;run;
proc contents data=pes;run;*/
```

VITA

Rachel K. Owen was born on August 18, 1990 in Des Moines, Iowa to parents Dina and Joel Johnson. She received her B.S. (Agronomy & Global Resource Systems) in 2013 from Iowa State University, Ames, Iowa. For her M.S., she joined South Dakota State University in 2013 and received the M.S. in Plant Science in 2014 under the supervision of Dr. Douglas Malo. She has accepted a Ph.D. position in the Department of Soils, Environmental and Atmospheric Sciences, University of Missouri, Columbia, where she will be moving after her graduation.